VOLUME 105 PART A NUMBER 24 DECEMBER 1958

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

SAVOY PLACE · LONDON WC.2.

Price Ten Shillings and Sixpence

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871 INCORPORATED BY ROYAL CHARTER 1921

PATRON: HER MAJESTY THE QUEEN

COUNCIL 1958–1959

President

S. E. GOODALL, M.Sc.(Eng.).

Past-Presidents

W. H. ECCLES, D.Sc., F.R.S.
THE RT. HON. THE EARL OF MOUNT EDGCUMBE, T.D.
J. M. DONALDSON, M.C.
PROFESSOR E. W. MARCHANT, D.Sc.
H. T. YOUNG.
SIR GEORGE LEE, O.B.E., M.C.
SIR ARTHUR P. M. FLEMING, C.B.E., D.Eng., LL.D.
J. R. BEARD, C.B.E., M.Sc.
SIR NOEL ASHBRIDGE, B.Sc.(Eng.).
COLONEL SIR A. STANLEY ANGWIN, K.C.M.G., K.B.E., D.S.O., M.C., T.D., D.Sc.(Eng.).
SIR HARRY RAILING, D.Eng.
P. DUNSHEATH, C.B.E., M.A., D.Sc.(Eng.).
SIR VINCENT Z. DE FERRANTI, M.C.
T. G. N. HALDANE, M.A.
PROFESSOR E. B. MOULLIN, M.A., Sc.D., LL.D.
SIR ARCHIBALD J. GILL, B.Sc.(Eng.).
SIR JOHN HACKING.
COLONEL B. H. LEESON, C.B.E., T.D.
SIR HAROLD BISHOP, C.B.E., B.Sc.(Eng.).
SIR JOSIAH ECCLES, C.B.E., D.Sc.
SIR GEORGE H. NELSON, Bart.
SIR GORDON RADLEY, K.C.B., C.B.E., Ph.D.(Eng.).
T. E. GOLDUP, C.B.E.

Vice-Presidents

SIR WILLIS JACKSON, D.Sc., D.Phil., Dr.Sc.Tech., F.R.S.
G. S. C. LUCAS, O.B.E.
SIR HAMISH D. MACLAREN, K.B.E., C.B., D.F.C., LL.D., B.Sc.
C. T. MELLING, C.B.E., M.Sc.Tech.
A. H. MUMFORD, O.B.E., B.Sc.(Eng.).

Honorary Treasurer

E. LEETE.

Ordinary Members of Council

J. A. BROUGHALL, B.Sc.(Eng.).
PROFESSOR M. W. HUMPHREY DAVIES, M.Sc.
SIR JOHN DEAN, B.Sc.
B. DONKIN, B.A.
J. M. FERGUSON, B.Sc.(Eng.).
D. C. FLACK, B.Sc.(Eng.), Ph.D.
J. S. FORREST, D.Sc., M.A.
R. J. HALSEY, C.M.G., B.Sc.(Eng.).
E. M. HICKIN.
J. B. HIGHAM, Ph.D., B.Sc.
F. C. MCLEAN, C.B.E., B.Sc.
B. L. METCALF, B.Sc.(Eng.).
J. R. MORTLOCK, Ph.D., B.Sc.(Eng.).
R. H. PHILLIPS, T.D.
H. V. PUGH.
J. R. RYLANDS, M.Sc., J.P.
D. P. SAYERS, B.Sc.
C. E. STRONG, O.B.E., B.A., B.A.I.
D. H. TOMPSETT, B.Sc.(Eng.).
H. WATSON-JONES, M.Eng.
H. WEST, M.Sc.

Chairmen and Past-Chairmen of Sections

Measurement and Control:
J. K. WEBB, M.Sc.(Eng.), B.Sc.Tech.
*H. S. PETCH, B.Sc.(Eng.).

Radio and Telecommunication:
G. MILLINGTON, M.A., B.Sc.
*J. S. MCPETRIE, Ph.D., D.Sc.

Supply:
D. P. SAYERS, B.Sc.
*PROFESSOR M. G. SAY, Ph.D., M.Sc., F.R.S.E.

Utilization:
R. A. MARRYAT, B.Sc.(Eng.).
*J. VAUGHAN HARRIES.

Chairmen and Past-Chairmen of Local Centres

East Midland Centre:
D. E. LAMBERT, B.Sc.(Eng.).
*J. D. PIERCE.

Mersey and North Wales Centre:
J. COLLINS.
*T. MAKIN.

North Midland Centre:
J. D. NICHOLSON, B.Sc.
*A. J. COVENEY.

North-Eastern Centre:
A. T. CRAWFORD, B.Sc.
*T. W. WILCOX.

Southern Centre:
G. BISHOP, B.Sc.
*L. G. A. SIMS, D.Sc., Ph.D.

North-Western Centre:
PROFESSOR F. C. WILLIAMS, O.B.E., D.Sc., D.Phil., F.R.S.
*F. R. PERRY, M.Sc.Tech.

Northern Ireland Centre:
D. S. MCILLHAGGER, Ph.D., M.Sc.
*C. M. STOUPE, B.Sc.

Western Centre:
R. W. STEEL.
*J. F. WRIGHT.

Scottish Centre:
R. J. RENNIE, B.Sc.
*E. O. TAYLOR, B.Sc.

South Midland Centre:
J. ASHMORE.
*L. L. TOLLEY, B.Sc.(Eng.).

* Past Chairman.

MEASUREMENT AND CONTROL, SUPPLY AND UTILIZATION SECTION COMMITTEES 1958–1959

Measurement and Control Section

Chairman
J. K. WEBB, M.Sc.(Eng.), B.Sc.Tech.

Vice-Chairmen
PROFESSOR A. TUSTIN, M.Sc.; C. G. GARTON.

Past-Chairmen
H. S. PETCH, B.Sc.(Eng.); DENIS TAYLOR, M.Sc., Ph.D.

Ordinary Members of Committee

E. W. CONNON, B.Sc.(Eng.), M.Eng.
W. S. ELLIOTT, M.A.
W. C. LISTER, B.Sc.
A. C. LYNCH, M.A., B.Sc.
A. J. MADDOCK, D.Sc.
R. E. MARTIN.
R. S. MEDLOCK, B.Sc.
A. NEMET, Dr.Ing.
G. A. W. SOWTER, Ph.D., B.Sc.(Eng.).
R. H. TIZARD, B.A.
F. C. WIDDIS, B.Sc.(Eng.).
M. V. WILKES, M.A., Ph.D., F.R.S.

And

The President (*ex officio*).
The Chairman of the Papers Committee.
J. B. HIGHAM, Ph.D., B.Sc. (representing the Council.)
W. GRAY (representing the North-Eastern Radio and Measurement Group).
T. KILBURN, M.A., Ph.D., D.Sc. (representing the North-Western Measurement and Control Group.)
G. H. RAYNER, B.A. (nominated by the National Physical Laboratory).
H. M. GALE, B.Sc.(Eng.) (representing the South Midland Radio and Measurement Group).

Supply Section

Chairman
D. P. SAYERS, B.Sc.

Vice-Chairmen
J. S. FORREST, D.Sc., M.A.; J. R. MORTLOCK, Ph.D., B.Sc.(Eng.); J. E. L. ROBINSON, M.Sc.

Past-Chairmen
PROFESSOR M. G. SAY, Ph.D., M.Sc., F.R.S.E.; P. J. RYLE, B.Sc.(Eng.).

Ordinary Members of Committee

F. H. S. BROWN, B.Sc.
G. S. BUCKINGHAM, B.Sc.(Eng.).
W. J. CARFRAE, B.Sc.
J. L. EGGINTON, B.Sc.
C. H. FLURSCHEIM, B.A.
P. M. HOLLINGSWORTH, M.Eng.
O. W. MINSHULL, B.Sc.
W. J. NICHOLLS, B.Sc.
J. E. PETERS, B.Sc.Tech.
E. P. G. THORNTON.
F. C. WALMSLEY.
A. L. WILLIAMS, Ph.D., M.Sc.

And

The President (*ex officio*).
The Chairman of the Papers Committee.
H. V. PUGH, (representing the Council).
J. WHITFIELD (representing the North-Western Supply Group).
R. A. YORK, B.Sc. (representing the South Midland Supply and Utilization Group).
A. G. MILNE (representing the Western Supply Group).

Utilization Section

Chairman
R. A. MARRYAT, B.Sc.(Eng.).

Vice-Chairmen
J. M. FERGUSON, B.Sc.(Eng.); T. E. HOUGHTON, M.Eng.

Past-Chairmen
J. VAUGHAN HARRIES; H. J. GIBSON, B.Sc.

Ordinary Members of Committee

B. ADKINS, M.A.
H. H. C. BARTON, B.A.
J. W. BINNS.
C. M. COCK.
W. J. GIBBS, D.Sc.
LT.-COL. R. J. HARDING, T.D.
J. B. LANCASTER, B.Sc.
R. P. MCCULLOCH, B.Eng.
P. MCKEARNEY, O.B.E.
R. F. RICHARDSON, M.B.E.
W. G. THOMPSON, Ph.D., B.Sc.
C. D. WILKINSON.

And

The President (*ex officio*).
The Chairman of the Papers Committee.
B. L. METCALF, B.Sc. (Eng.) (representing the Council).
C. E. DEW (representing the Western Utilization Group).
J. N. M. LEGATE, B.Sc. (representing the North-Western Utilization Group).
J. R. ANDERSON, T.D., B.Sc.(Eng.) (representing the South Midland Supply and Utilization Group).
A. R. RUMFITT (representing the North Midland Utilization Group).

The following nominees of Government Departments:

Admiralty: P. SMITH, B.Sc.
Air Ministry: H. F. INNOCENT.
Ministry of Labour and National Service (Factory Dept.): S. J. EMERSON, M.Eng.
Ministry of Works: P. MCKEARNEY.
War Office: LT.-COL. R. F. PRATT, B.A., R.E.

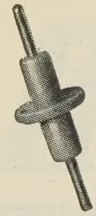
Secretary

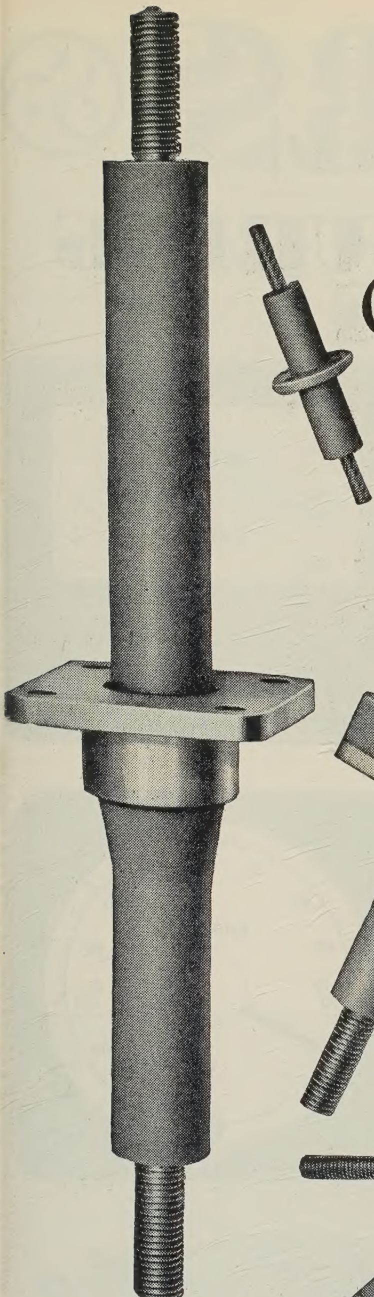
W. K. BRASHER, C.B.E., M.A., M.I.E.E.

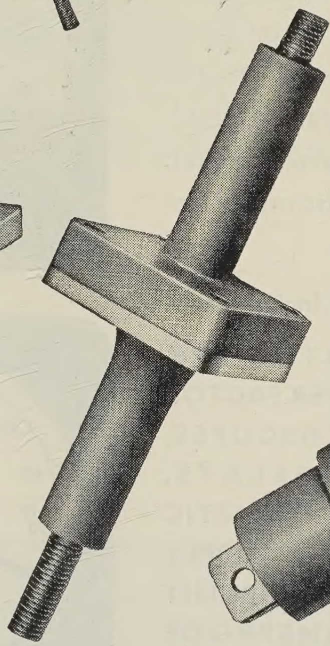
Deputy Secretary
F. JERVIS SMITH, M.I.E.E.

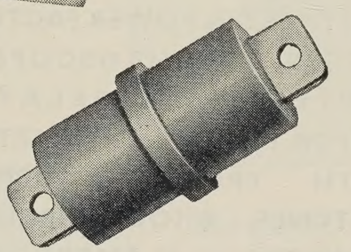
Assistant Secretary
F. C. HARRIS.

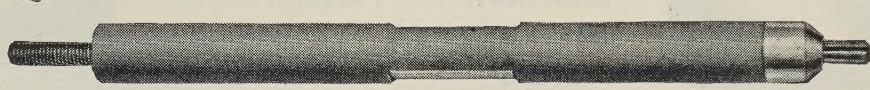
Editor-in-Chief
G. E. WILLIAMS, B.Sc.(Eng.), M.I.E.E.

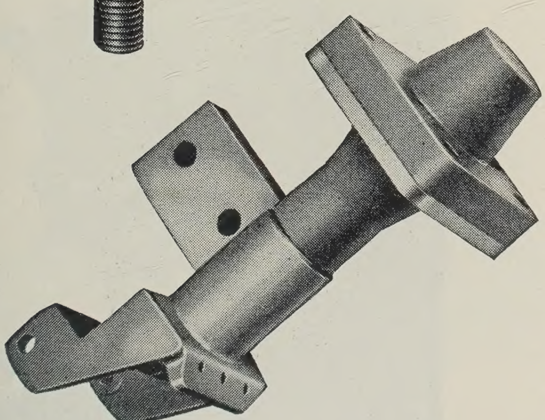












Current Practice

Araldite epoxy resins provide the answer to many problems encountered in the manufacture of electrical equipment. Bushings are a good example. Made with Araldite, they exploit the outstanding properties of the epoxies—remarkable void-free adhesion to metal, outstanding anti-tracking qualities, high mechanical strength, low shrinkage, stability, resistance to climatic conditions and chemicals and excellent dielectric properties. The components shown are cast bushings for use in air, oil or compound on potentials up to 11,000 V, and are manufactured by J. R. Ferguson (Electrical Engineers) Limited, Dukinfield, Cheshire.

Araldite epoxy resins are used

- ★ **for bonding metals, porcelain, glass, etc.**
- ★ **for casting high grade solid electrical insulation**
- ★ **for impregnating, potting or sealing electrical windings and components**
- ★ **for producing glass fibre laminates**
- ★ **for producing patterns, models, jigs and tools**
- ★ **as fillers for sheet metal work**
- ★ **as protective coatings for metals, wood and ceramic surfaces**

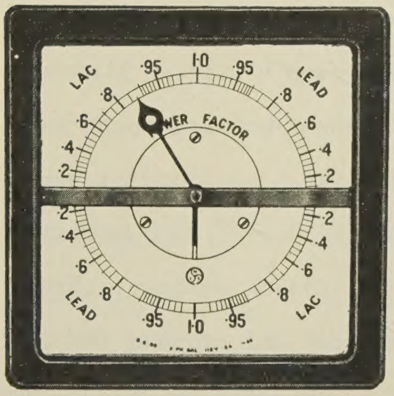
Araldite *epoxy resins*

Araldite is a registered trade name

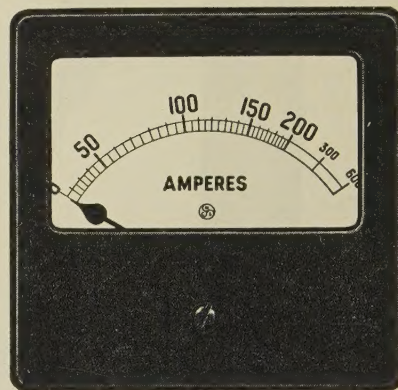
CIBA (A.R.L.) LIMITED Duxford, Cambridge. Telephone: Sawston 2121

NALDERS

ELECTRICAL MEASURING INSTRUMENTS

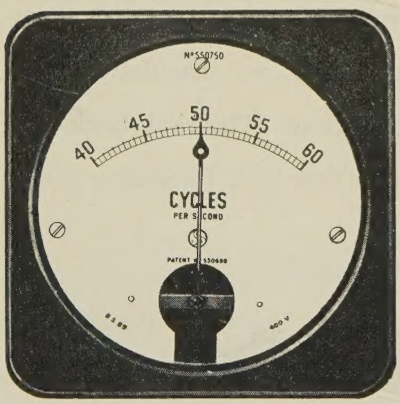


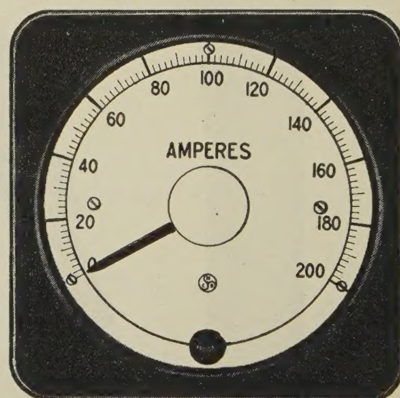
Nalders manufacture a wide range of Measuring Instruments, Indicating, Recording, Switchboard and Portable. Cases are of rectangular, square or round pattern in die-cast aluminium or pressed steel, finished bright black stove enamel, or other colour to customers' requirements.



Nalder's Products include:

AMMETERS, VOLTMETERS, WATTMETERS, POWER FACTOR METERS, SYNCHROSCOPES, PROTECTIVE RELAYS, VECTOR METERS, AUTOMATIC EARTH PROVING SUPPLY SWITCHES, 'BIJOU' CIRCUIT BREAKERS, FLAMEPROOF INSTRUMENTS, FREQUENCY METERS



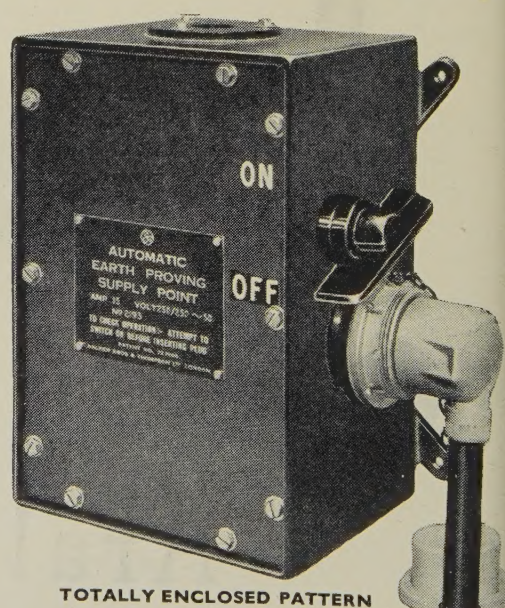


AUTOMATIC EARTH PROVING SWITCHES

Protect operators by ensuring the continuity of Earth Connection for all Portable Tools so that no Tool can be energised unless the Earth Lead is intact. The switch provides a Supply Point which secures the immediate isolation of any suitably wired Tool should its earthing become defective.

We can meet your demands for

PROMPT DELIVERY OF ALL PRODUCTS

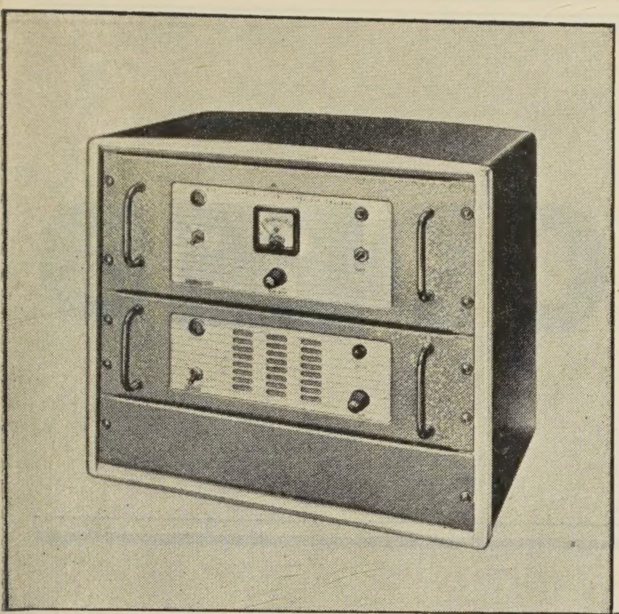


TOTALLY ENCLOSED PATTERN

NALDER BROS. & THOMPSON LTD., Dalston Lane Works, London, E.8

Telephone: Clissold 2365 (4 lines)

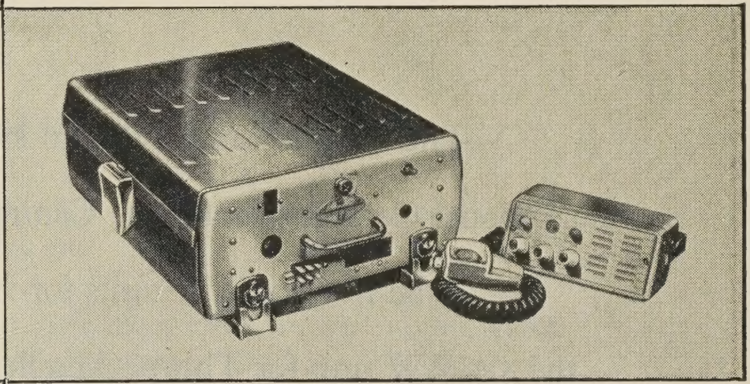
Telegrams: "Occlude, Hack, London"

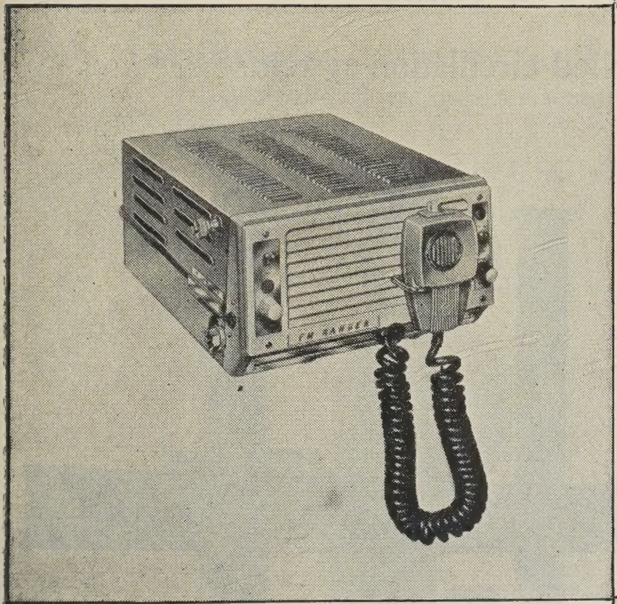


BY APPOINTMENT
TO H.R.H. DUKE OF EDINBURGH
SUPPLIERS OF
RADIO TELEPHONE EQUIPMENT
PYE TELECOMMUNICATIONS LTD.

ANNOUNCING THE LATEST RANGER RADIOTELEPHONES

A complete series of fixed and mobile equipment AM or FM





MAIN FEATURES:

- Available from 25 Mc/s to 174 Mc/s.
- F.M. or A.M. simplex or duplex
- Low battery drain
- Split-channel selectivity
- Unit chassis construction
- Up to 6 switch-selected channels
- Light weight
- Low cost installation and maintenance

The following features are optional:

Channel spacing. A.M. Type V: 20, 25, 30 kc/s. Type N: 40, 50, 60 kc/s; Type W: 100 kc/s or greater. F.M. Types: 40, 50 or 60 kc/s. Public address and Re-broadcast facility on A.M. Types. Fist microphone or telephone handset.

Mobile Ranger Equipment

PTC 2001/2 5 watt A.M. Dash-Mounted Unit
PTC 2101/2 5 watt A.M. Boot-Mounted Unit
PTC 2201/2 15 watt A.M. Boot-Mounted Unit
PTC 8001/2 10 watt F.M. Dash-Mounted Unit
PTC 8101/2 10 watt F.M. Boot-Mounted Unit
PTC 8201/2 20 watt F.M. Boot-Mounted Unit

Fixed Stations

PTC 743/4 15 watt A.M. Fixed Station
PTC 753/4 50 watt A.M. Fixed Station
PTC 8701/2 20 watt A.M. Fixed Station

PYE TELECOMMUNICATIONS LTD
NEWMARKET ROAD
CAMBRIDGE
Telephone: TEVERSHAM 3131
Cables: PYETELECOM CAMBRIDGE

PYE

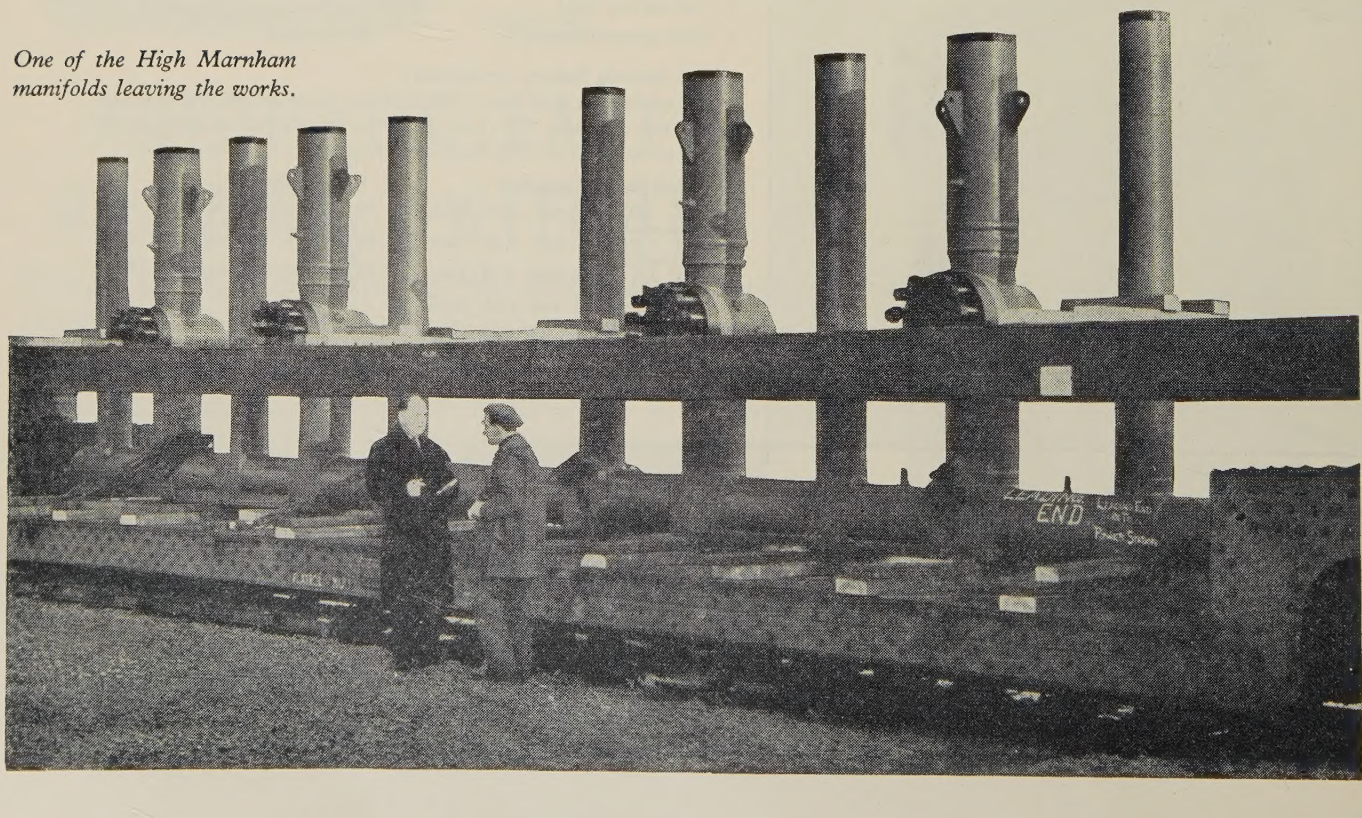
All Ranger Mobile Models are available for 6, 12 or 24 volts power supplies.

Please write for further details

CONTROLLED

The most advanced design steam raising units to be built by International Combustion for the Central Electricity Generating Board —the five 200MW units for High Marnham Power Station and the 550MW unit for Thorpe Marsh Power Station —will employ the controlled circulation system.

One of the High Marnham manifolds leaving the works.



CIRCULATION

STUDY THESE FEATURES

- **POSITIVE CIRCULATION** Positive and adequate circulation is assured to each and every tube, irrespective of firing rate.
- **LOWER STRESSES** The smaller bore tubes which are used in this system permit thinner walls and lower metal temperatures.
- **QUICKER STARTING** Positive circulation both from cold or banked conditions ensures equal and even temperatures throughout the unit.
- **ECONOMY** The effective use of heating surfaces and their disposition permit lighter structures, with economy of space occupation and civil engineering costs.

IC

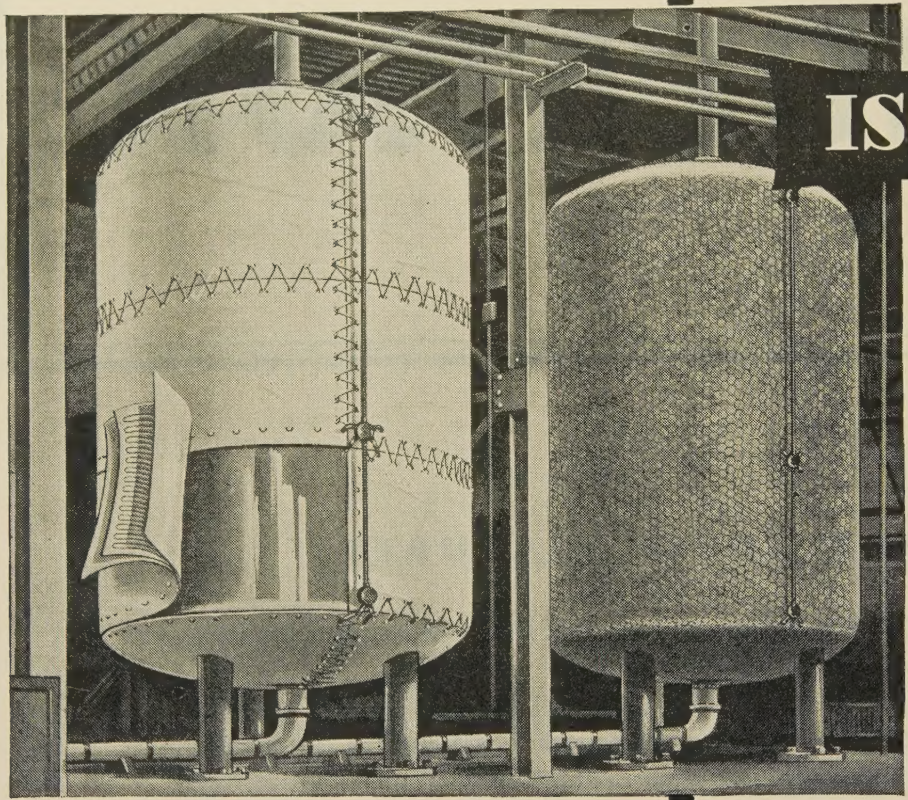
INTERNATIONAL COMBUSTION LIMITED

LONDON OFFICE: NINETEEN WOBURN PLACE WC1 · TELEPHONE TERMINUS 2833 · WORKS: DERBY

Member of Atomic Power Constructions Ltd. One of the five British Nuclear Energy Groups

TGA 5G73A

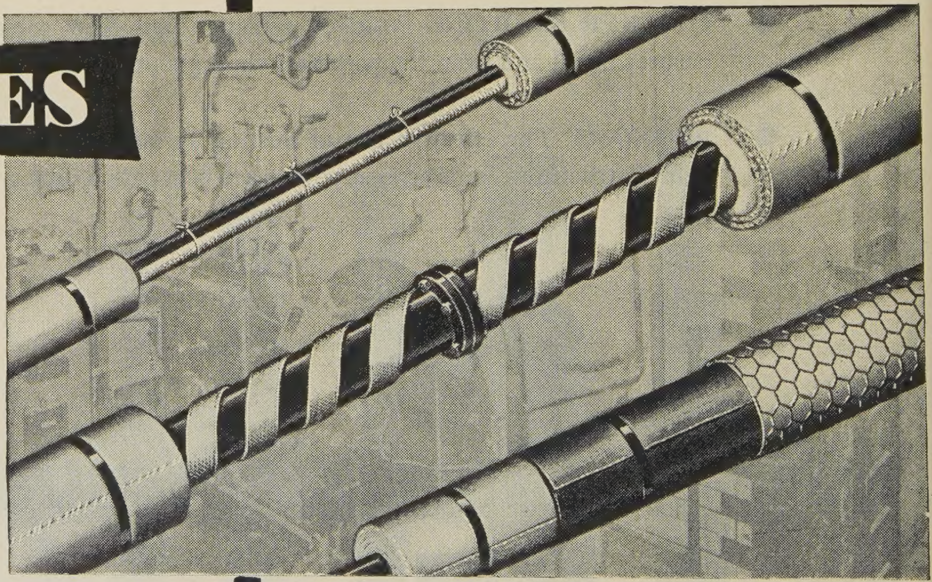
For maintaining correct temperatures...



ISOPANELS

FOR STORAGE TANKS

Fully flexible, made from glass yarn interwoven with insulated heating cord, these electric heaters can be adapted to any shape and size of container. Slots and cut-outs can be made to allow for outlet pipes, manholes, or supports.



ISOTAPES

FOR PIPE TRACING

The wide range of tapes from 1′ 6″ to 240′ length in five loadings from 5 to 40 watt per foot allows you to choose the correct unit for any heating or compensating duty. Easily and quickly applied, terminations at one end. Please ask for PLT/58—new 44 page Plant catalogue fully documenting our Surface Heating Units

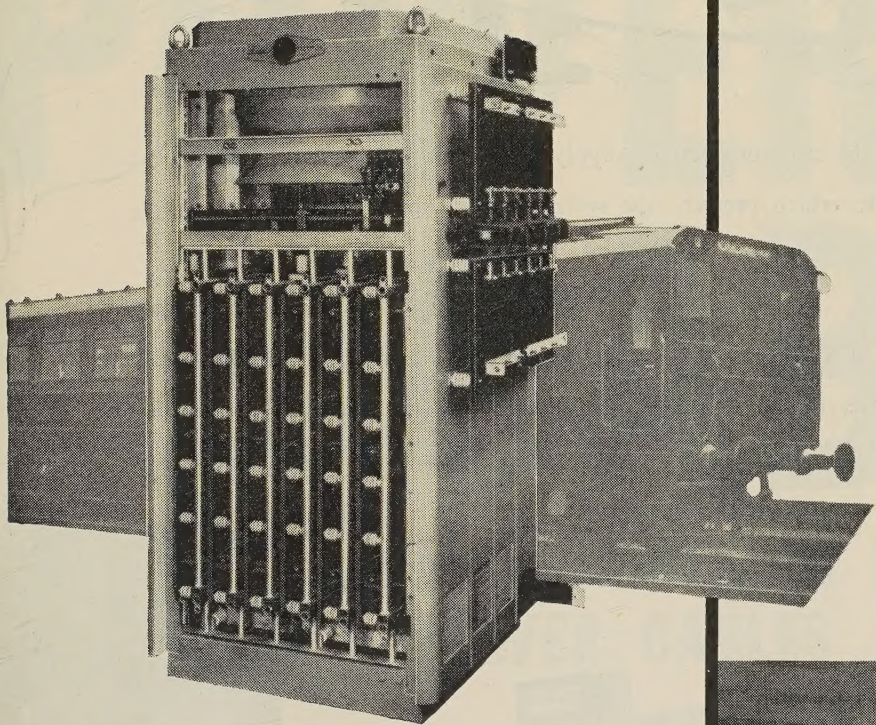
ISOPAD ELECTRIC SURFACE HEATERS

ISOPAD LTD., BARNET BY-PASS, BOREHAM WOOD, HERTS Telephone: ELStree 2817/8/9

LEADERSHIP

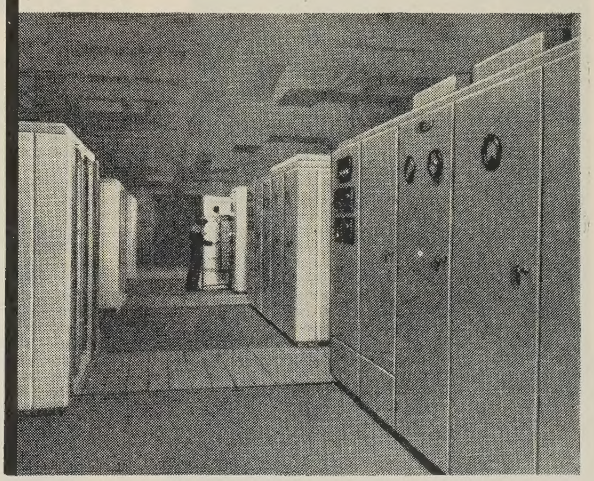
in

SEMI-CONDUCTOR POWER RECTIFIERS



SILICON

The first traction silicon rectifier in Great Britain—installed in a motor-coach on the Lancaster/Morecambe/Heysham line of British Railways.



GERMANIUM

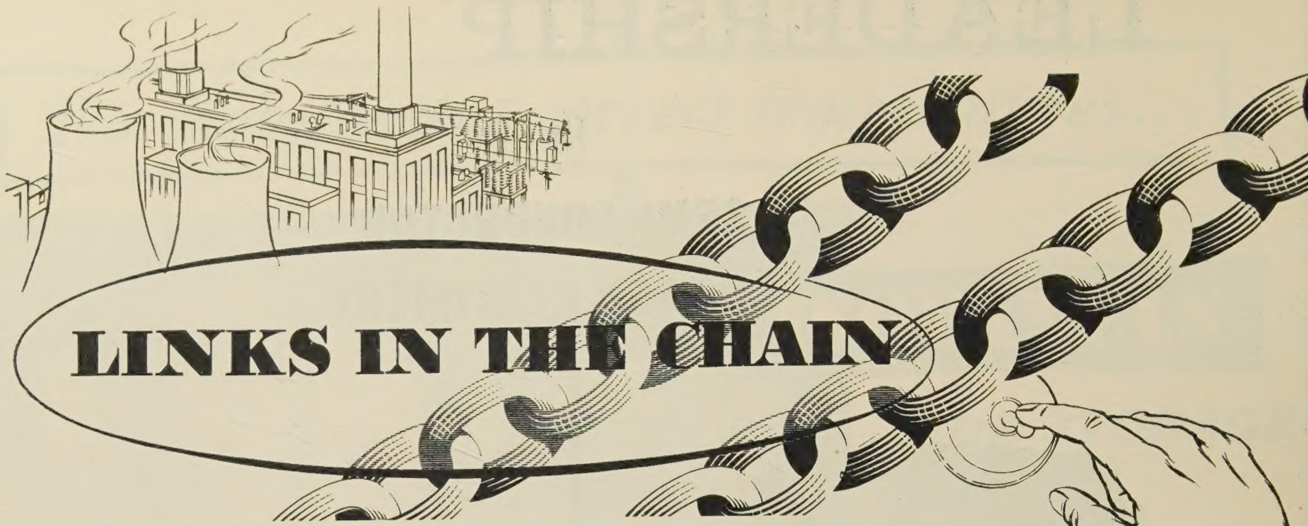
Part of an 18,400 kW germanium power rectifier installation rated at 80,000 amp., 230 volts—one of the largest operating in the world.

A·E·I HEAVY PLANT DIVISION

RUGBY & MANCHESTER, ENGLAND

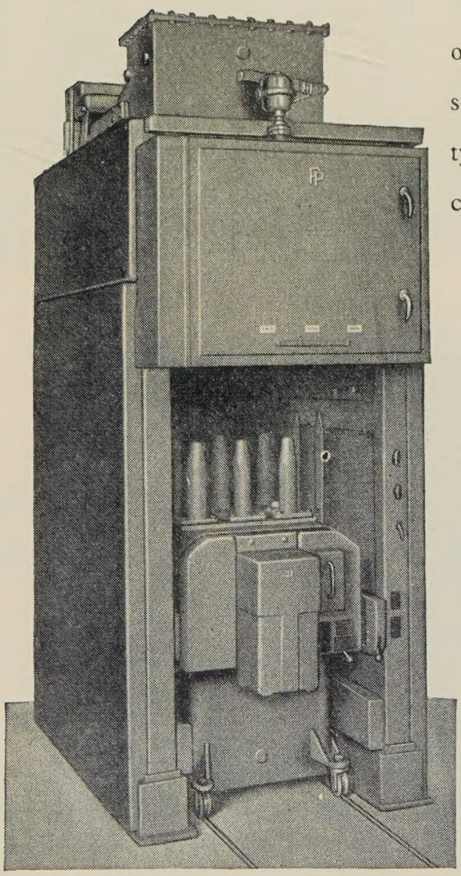
A DIVISION OF ASSOCIATED ELECTRICAL INDUSTRIES LTD., incorporating the interests of BTH & MV

A5301

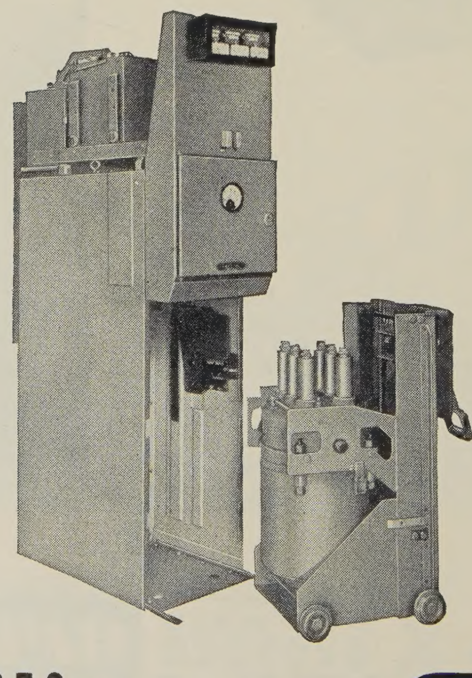


Of the many links in the chain of electrical supply, none is of greater importance than SWITCHGEAR, which protects the system against short-circuit or other abnormal conditions.

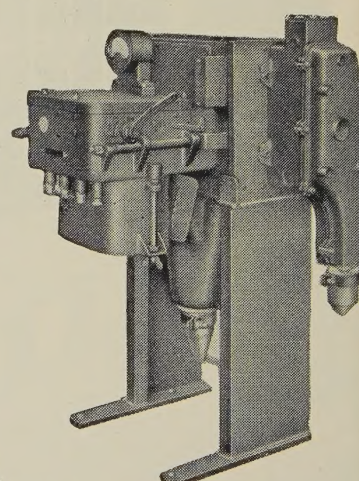
"Ferguson Pailin" have a high reputation for the manufacture of Switchgear of all ratings, from that designed for extra high voltage service within the 'Supergrid', down to medium voltage or industrial type Switchgear which may be found in service in factories and commercial buildings everywhere.



Type VSLP9 Switchgear, rated 1000-MVA breaking capacity at 33-kV.



Type BV Switchgear for 11-kV service up to 250-MVA breaking capacity.



Type K3 pedestal mounted switchgear for service up to 400-A 660-V

Ferguson Pailin LIMITED *for Switchgear*

An A.E.I. Company

Head Office & Works: **HR. OPENSHAW MANCHESTER 11,** *Telephone :* DROylsden 1301 (Pte.Branch Ex)

LONDON OFFICE : Bush House, Aldwych, W.C.2 BIRMINGHAM OFFICE : Windsor House, 656 Chester Road, Erdington, 23 GLASGOW OFFICE : Central Chambers, 109 Hope Street, C.2.

REPRESENTED IN PRINCIPAL OVERSEAS TERRITORIES

PVC POWER CABLES

MERSEY,
long established as a
leading manufacturer of
rubber insulated power cables,
also produce
a full range of

PVC INSULATED MEDIUM VOLTAGE POWER CABLES

Mersey's modern production techniques have produced a high quality low priced PVC power cable capable of withstanding rugged working conditions. Furthermore, Mersey offer the personal service of a medium size company coupled with the Research facilities and other Resources of the T.I. Group.

For further information about Mersey power cables, send for the illustrated catalogue No. D./102.

BY MERSEY

MERSEY CABLE WORKS LIMITED

Linacre Lane · Bootle · Liverpool 20

Telephone: Bootle 4111 · Telegrams: MERCABLES Liverpool 20

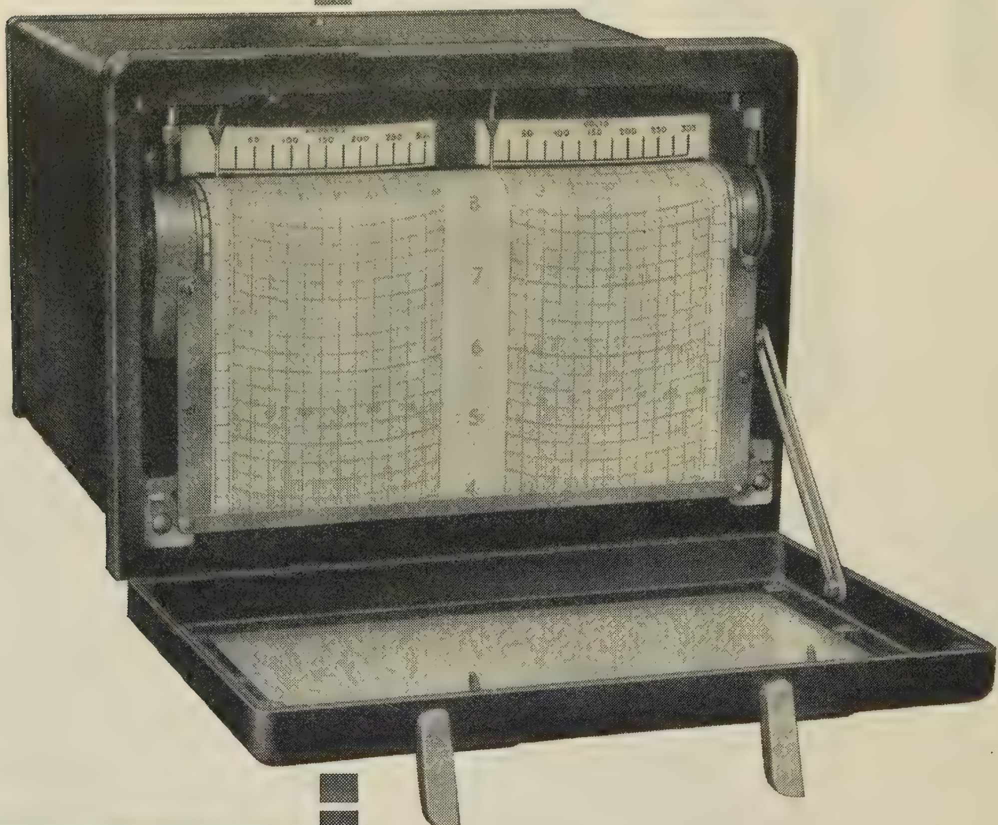
A TI COMPANY

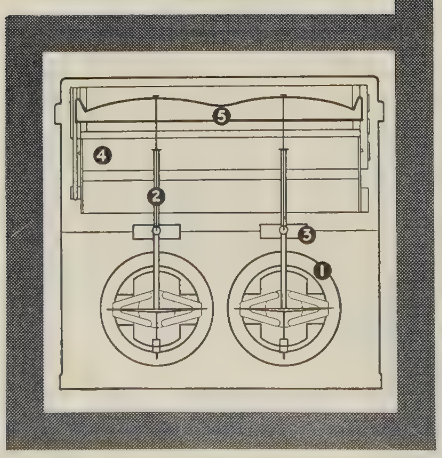
MCW21

RECORD

DUPLEX

GRAPHIC RECORDING INSTRUMENTS





Built to the same high standards and with the same outstanding performance as the single Graphic Recorder. Note the extremely compact space-saving layout.

1. Movements—high sensitivity, quick response.
2. Pen arms and Pens—capillary action.
3. Ink Troughs—almost unspillable.
4. Chart Mechanism—withdrawable for changing charts.
5. Scaleplate and Carrier.

Send for further details.

THE RECORD ELECTRICAL CO. LTD.

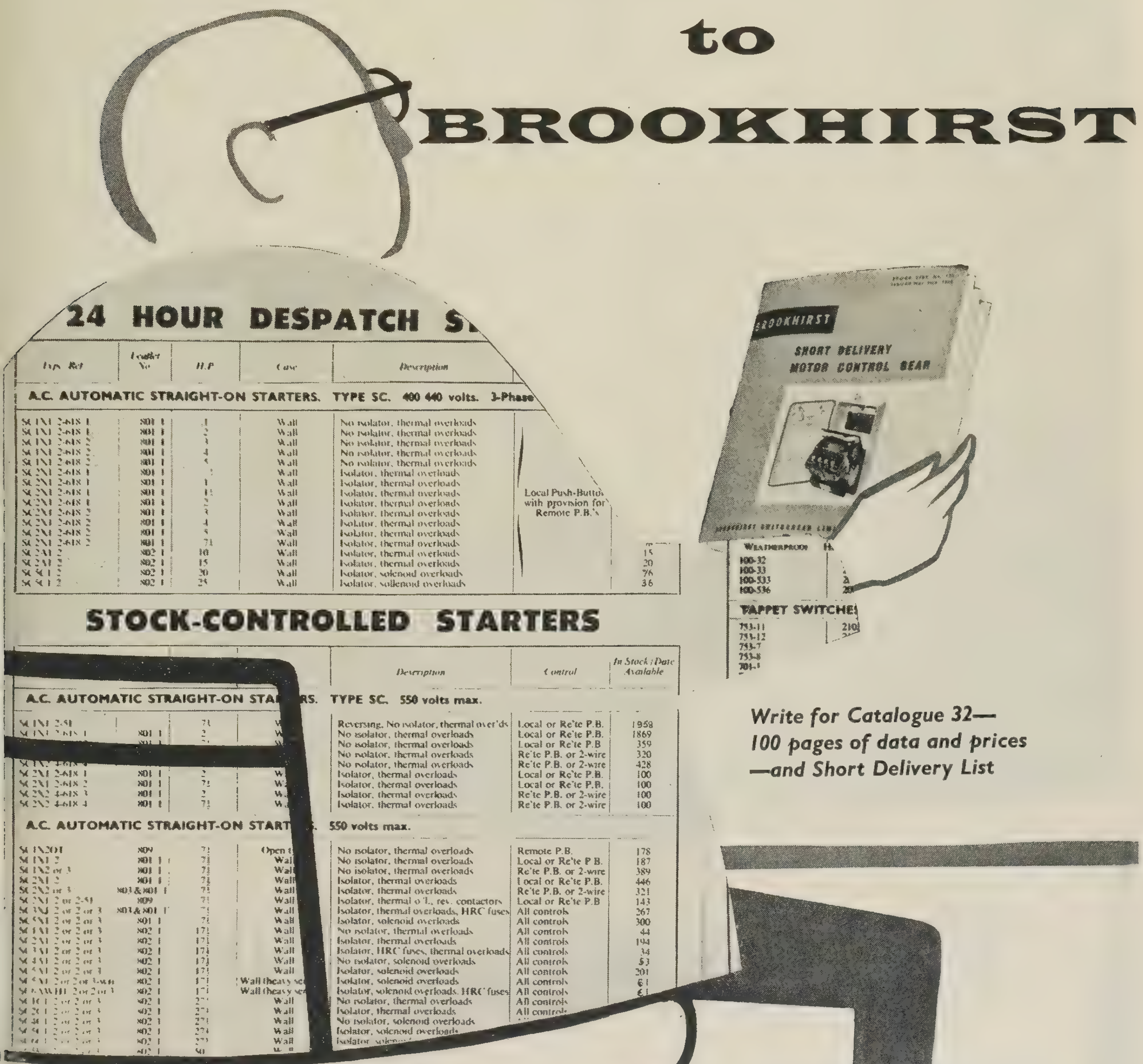
"CIRSCALE WORKS," BROADHEATH, ALTRINCHAM, CHESHIRE

Offices at: Belfast, Birmingham, Bristol, Dublin, Glasgow, Leeds, London

C8917-1

- For the widest choice in **STANDARD STARTERS**
- For adaptability within standardisation
- For quick delivery— 24 hour despatch of popular items

Look first to BROOKHIRST



Write for Catalogue 32— 100 pages of data and prices —and Short Delivery List

BROOKHIRST

SPECIALISTS IN MOTOR CONTROL

BROOKHIRST SWITCHGEAR LIMITED · NORTHGATE WORKS · CHESTER

A METAL INDUSTRIES GROUP COMPANY

CVS-63

'ENGLISH ELECTRIC'

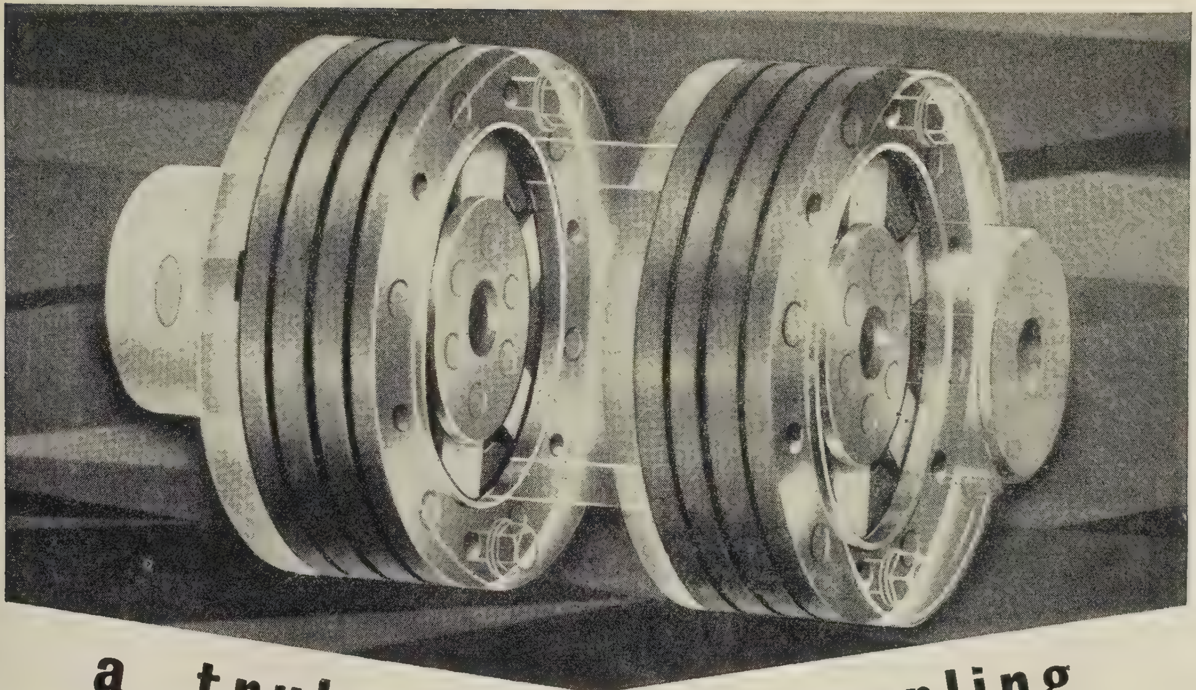
transformers

THE ENGLISH ELECTRIC COMPANY LIMITED, MARCONI HOUSE, STRAND, LONDON, W.C.2.

Transformer Department, Stafford

WORKS: STAFFORD · PRESTON · RUGBY · BRADFORD · LIVERPOOL · ACCRINGTON

TFS. 23L8



a truly flexible coupling

Stainless steel membranes put flexibility into Metastream Couplings—they provide lateral, angular and axial flexibility independent of the torque transmitted—they are corrosion resistant to a high degree and unaffected by operating temperatures and atmospheric conditions.

Prices Reduced. Improved manufacturing methods, increased production and lower cost of raw materials, enable the prices of the M-range of Metastream Couplings to be reduced by 10% below list.

METASTREAM

—the perfect coupling for the perfect drive

Does not require lubrication.

Simple all-metal construction.

No springs—gears—chains—rubber bushes—roller or sliding members.

No thrust transmitted.

M SERIES — *spacer and non-spacer*

LD SERIES — *light duty spacer*

SB SERIES — *non-spacer for single bearing units*

HS SERIES — *cardan shaft units*

There's a complete range of couplings for all duties and horse-powers. Please write for full details.

METADUCTS LIMITED

CATHERINE WHEEL ROAD, BRENTFORD, MIDDX. TELEPHONE EALING 3678

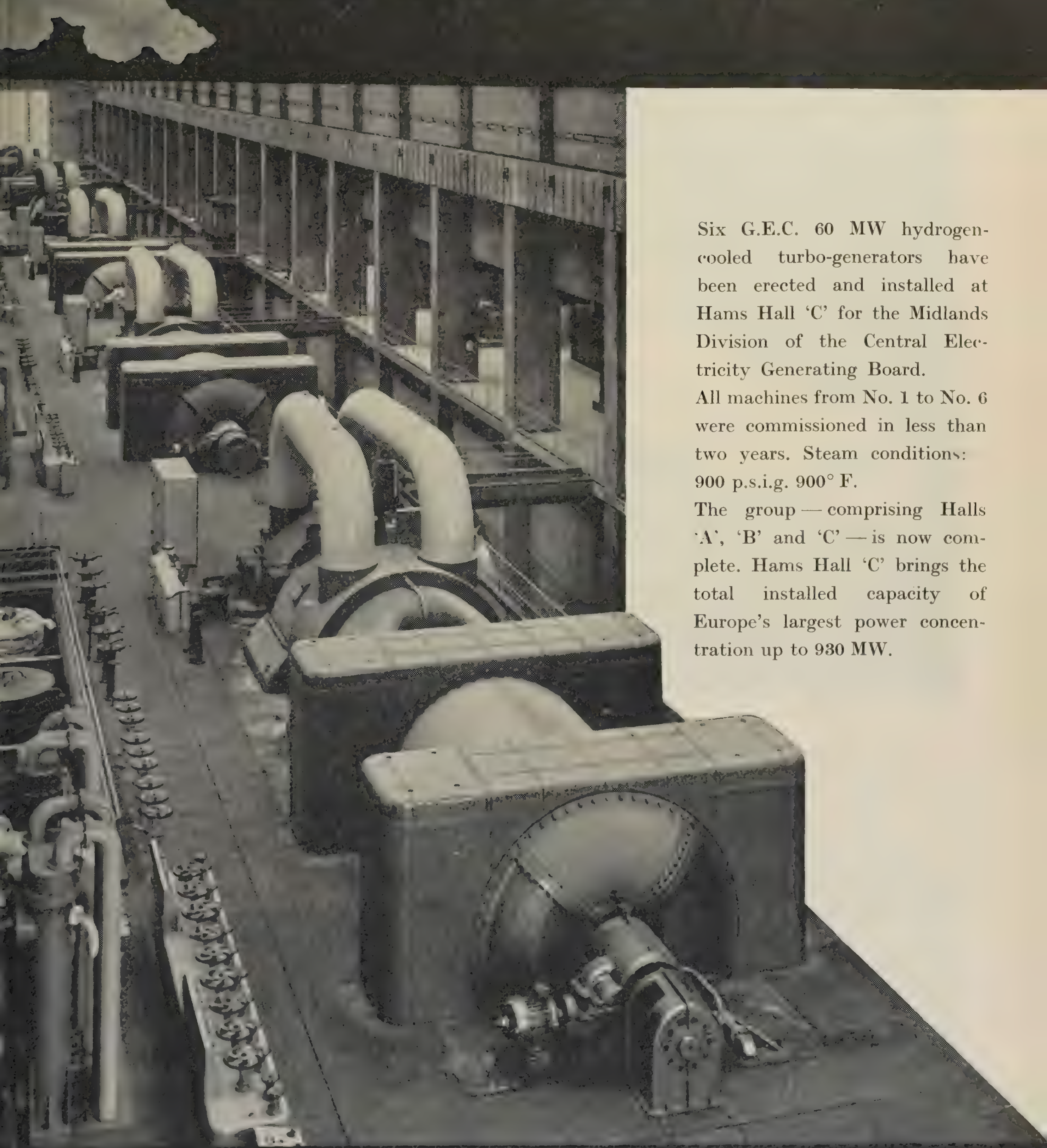
A MEMBER OF THE CONCENTRIC GROUP OF COMPANIES.

Six G.E.C. sets complete Europe's

Aerial view looking north of Hams Hall 'C'.

G.E.C.

largest power concentration



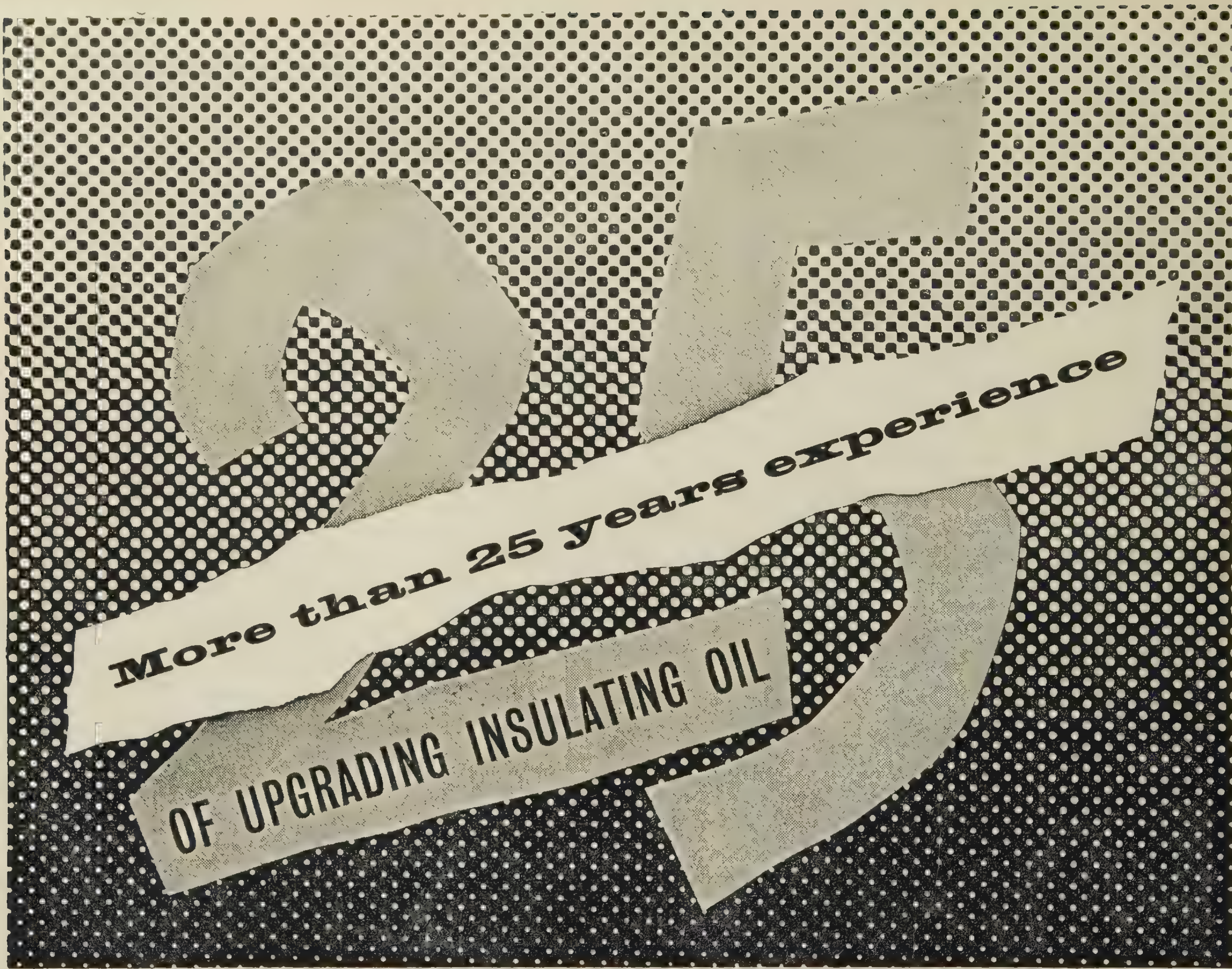
Six G.E.C. 60 MW hydrogen-cooled turbo-generators have been erected and installed at Hams Hall 'C' for the Midlands Division of the Central Electricity Generating Board.

All machines from No. 1 to No. 6 were commissioned in less than two years. Steam conditions: 900 p.s.i.g. 900° F.

The group — comprising Halls 'A', 'B' and 'C' — is now complete. Hams Hall 'C' brings the total installed capacity of Europe's largest power concentration up to 930 MW.

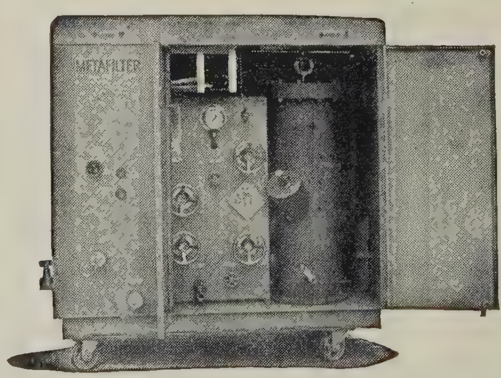
power generation

THE GENERAL ELECTRIC CO. LTD. OF ENGLAND, HEAD OFFICE: MAGNET HOUSE, KINGSWAY, LONDON, W.C.2



For more than a quarter of a century Metafilters have been accepted by electrical engineers for the COLD upgrading of switch and transformer oils. The filtration principle (using Metasil A.W.) is precisely the same as that employed for the removal of bacteria in other applications, thus ensuring absolute removal of solid impurities however finely divided, together with dehydration without recourse to heating and/or vacuum.

Electrical and consulting engineers, well-known oil companies, generating and distributing organisations, manufacturers of transformers and switchgear have chosen the Metafilter because (a) COLD filtration effects removal of impurities otherwise soluble in hot oil, (b) high di-electric strength and (c) no costly expenditure on replacement papers or sheets.



Metafilters for transformer and switch oils are available as static, portable and fully mobile units with capacities from 50 g.p.h. to 1000 g.p.h. Our experience and advice is at your disposal. Please write for Section 7 Catalogue giving details of our latest units.

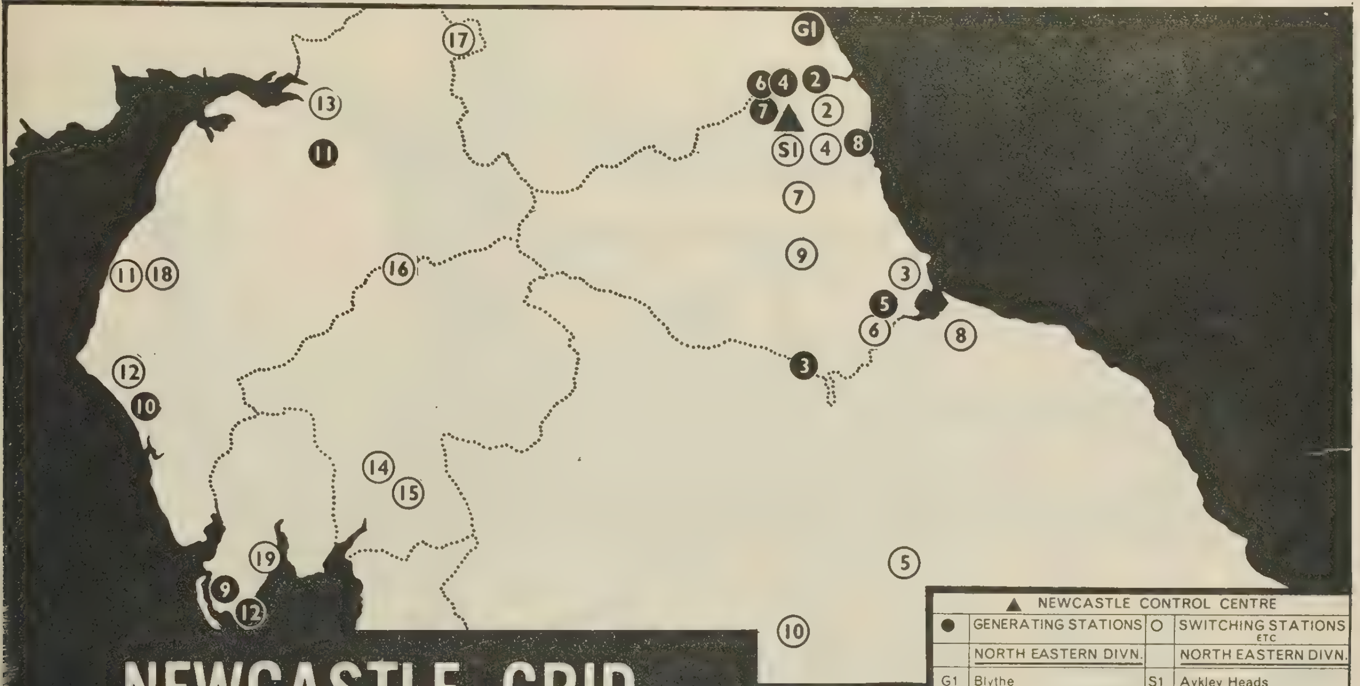
Metafilter

TRADE MARK

'PURITY WITH SIMPLICITY'

THE METAFILTRATION CO. LTD.
BELGRAVE RD., HOUNSLOW, MIDDX.
Phone: HOUnslow 1121-3

THE BRITISH ELECTRICITY GRID UNDER CONTROL



NEWCASTLE GRID CONTROL AREA

Installed by S.T.C. as the centralised control and indication centre for the Newcastle Grid Control Area of the British Central Electricity Generating Board. By a new "standardised system" of control the operation of the power stations and switching centres in the counties of Northumberland, Durham, Westmorland, Cumberland, Lancashire and Yorkshire is efficiently supervised and controlled to supply power to a population of approximately three million people.

▲ NEWCASTLE CONTROL CENTRE

●	GENERATING STATIONS	O	SWITCHING STATIONS ETC
	NORTH EASTERN DIVN.		NORTH EASTERN DIVN.
G1	Blythe	S1	Aykley Heads
G2	Carville	S2	Boldon
G3	Darlington	S3	Hartmoor
G4	Dunston	S4	Herrington Burn
G5	North Tees	S5	Husthwaite
G6	Stella North	S6	Norton
G7	Stella South	S7	Potter House
G8	Sunderland	S8	South Tees
		S9	Spennymoor
		S10	Wormald Green
	N WEST MERSEYSIDE & NORTH WALES DIVN.		N/WEST MERSEYSIDE & NORTH WALES DIVN.
G9	Barrow	S11	Distington
G10	Calderhall	S12	Egremont
G11	Carlisle	S13	Harker
G12	Rooscote	S14	Kendal
		S15	Natland
		S16	Penrith
		S17	Spadeadam
		S18	Stainburn
		S19	Ulverston

Newcastle Control Centre is one of the three control centres installed by S.T.C. for the Thames North, Leeds and Newcastle Control areas in the Central Electricity Generating Board's electricity supply system. This system with its national centre and seven local control centres is the largest system under unified control in the world, having 260 Power Stations and a total output of 24 000 MW. The new "standardised system" of control, general indicating, telephone and telemetering equipment has been developed jointly by the Generating Board and the three telephone manufacturers—Automatic Telephone and Electric Co. Ltd., the General Electric Co. Ltd., and Standard Telephones and Cables Ltd. In addition to the above schemes S.T.C. has played an important part in the remote control schemes for the North of Scotland Hydro Electric Board (NOSHEB), Snowy Mountain (Australia), Owen Falls (Uganda), Waipori (New Zealand), Aswan (Egypt) and Kariba (Rhodesia).

Newcastle Control Room

Standard Telephones and Cables Limited

Registered Office: Connaught House, Aldwych, London, W.C.2

TELEPHONE DIVISION: OAKLEIGH ROAD · NEW SOUTHGATE · LONDON N.11

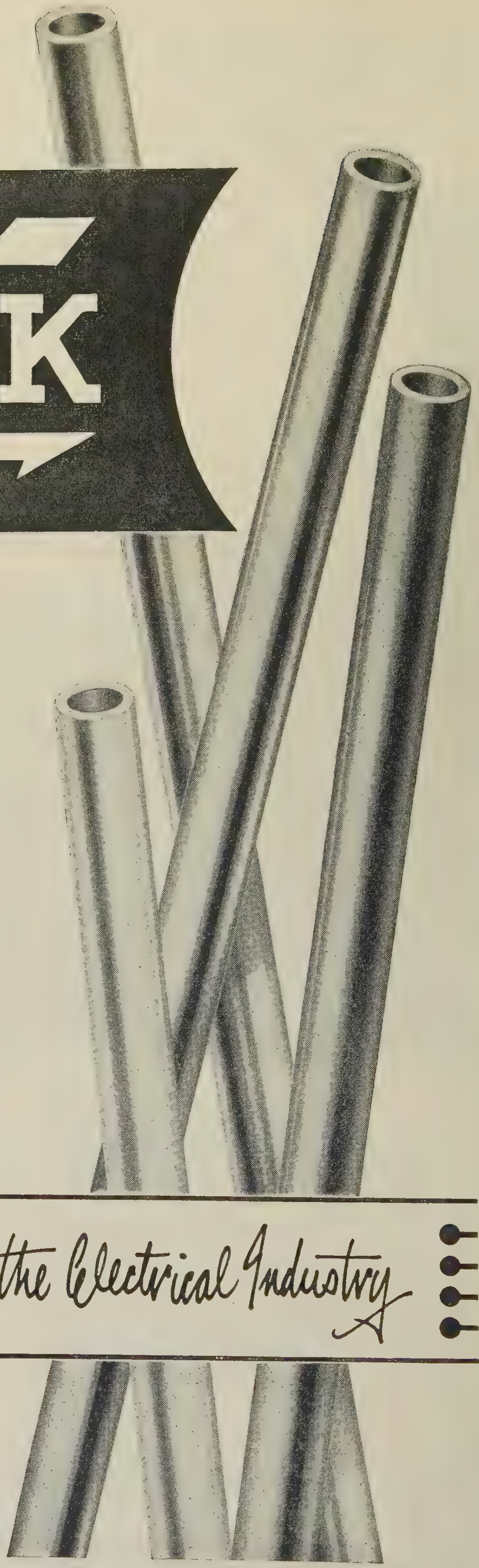
SERCK

SERCKALBRA
SERCKCUNIK
ADMIRALTY BRASS
ALUMINIUM BRONZE
70/30 BRASS

condenser tubes

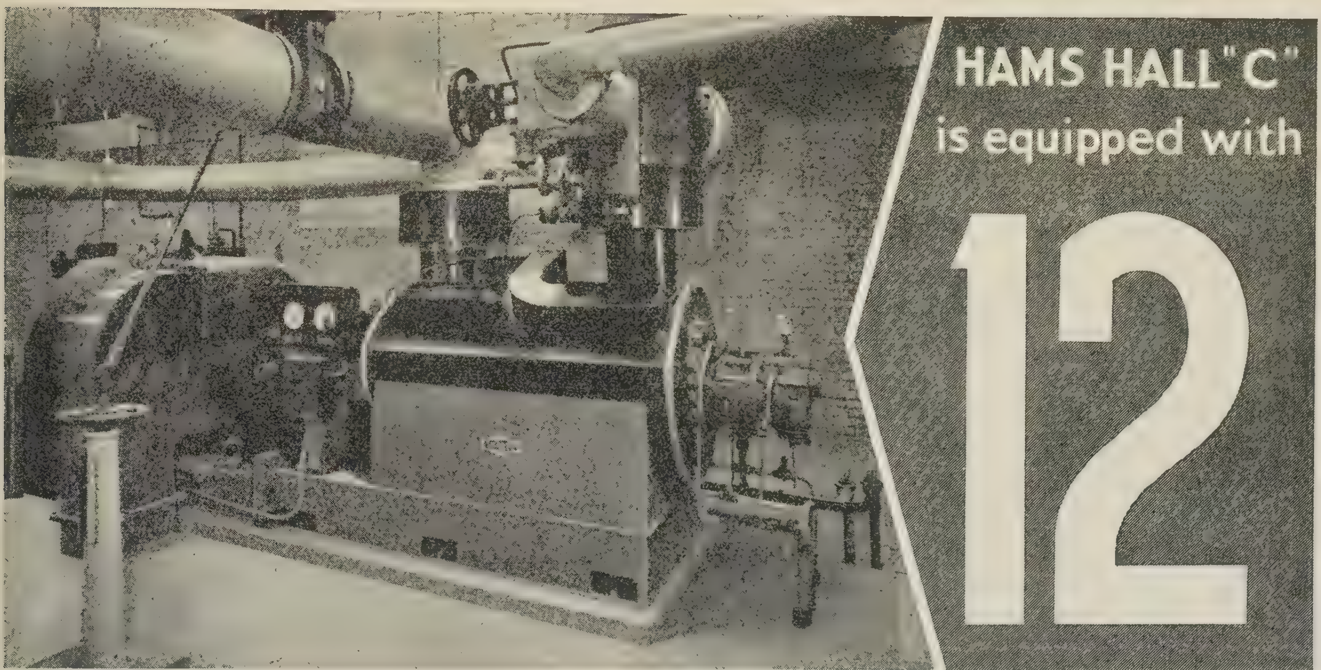
for the Electrical Industry

SERCK TUBES LIMITED, WARWICK ROAD, BIRMINGHAM 11



EUROPE'S LARGEST CONCENTRATION OF POWER

HAMS HALL "A" "B" & "C" BIRMINGHAM



One of the Weir Electrofeeders in Hams Hall "C" Power Station

Weir BOILER FEED PUMPS

Each of the twelve Weir Electrofeeders in the Central Electricity Generating Board's "C" station at Hams Hall, has a capacity of 650,000 lb./hr. at 1,210 lb./sq. in. with a suction temperature of 277°F.

Weir Turbine-Driven pumps are also in use in the "A" and "B" stations at Hams Hall.

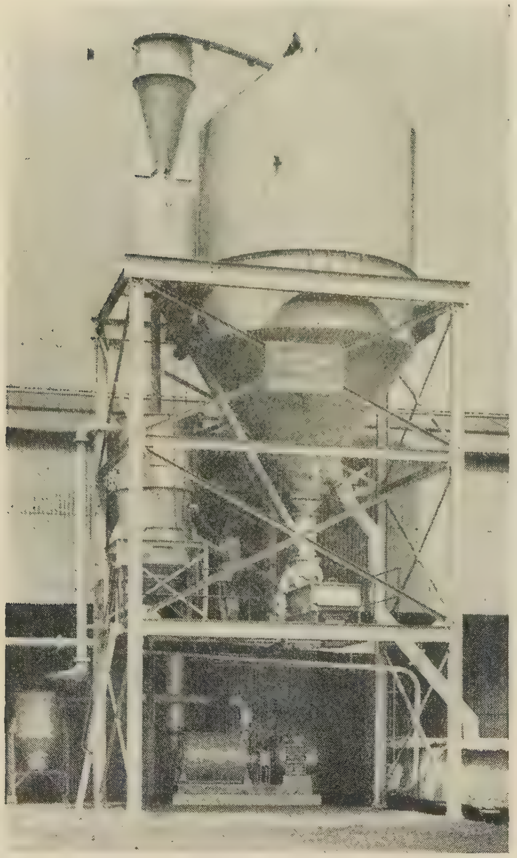
Weir

G. & J. WEIR LTD. · CATHCART · GLASGOW S.4

STURTEVANT

FLUE DUST EXTRACTION PLANT

for the



This illustration shows a plant for six stoker-fired boilers for process steam at a large paper mill. Dust and grit from the hoppers are collected at the rate of about four tons per hour. Plant includes a Sturtevant Turbo-Exhauster and Receiver and dust conditioner to prevent dust escaping to atmosphere when discharging into a disposal lorry.

CONTINUOUS **extraction o boiler flue dust and grit whilst under steaming conditions.**

- **Eliminates manhandling of dust an grit.**
- **Gives cleaner conditions in th boiler house.**
- **Conveys dust and grit direct fro hoppers to central receiver.**

With the addition of a small bore piping syste complete vacuum cleaning of all surfaces can b carried out from hose connections placed a convenient points.

Particulars may be obtained by writing t reference N/101/CWB.

STURTEVANT ENGINEERING CO. LTD.
Southern House, Cannon Street, LONDON, E. C. 4.

AUSTRALIA: STURTEVANT ENGINEERING CO. (AUSTRALASIA) LTD. 400 SUSSEX STREET SYDNEY N.S.W.

THEY SET A STANDARD

OVER 1500 years ago the Romans built the roads whose names are still familiar to us—Fosse Way, Watling Street, Icknield Way, Ermine Street and many others. Often following tracks old before the Romans came, these broad, straight roads provided vital communication for the legions, and for the administrators and merchants who followed in their steps. In road building, as in many other fields, the Romans set a standard which few have equalled since.

In cable making, too, standards are of vital importance. For over 100 years members of the Cable Makers Association have been concerned in all major advances in cable making. Together they spend over one million pounds a year on research and development. The knowledge gained is available to all members. This co-operation has contributed largely to the world-wide prestige that C.M.A. cables enjoy, and it has put Britain at the head of the world cable exporters.

Technical information and advice is freely available from any C.M.A. member.

Roman legionaries on the march.

MEMBERS OF THE C.M.A.

British Insulated Callender's Cables Ltd · Connollys (Blackley) Ltd · Enfield Cables Ltd · W. T. Glover & Co. Ltd · Greengate & Irwell Rubber Co. Ltd. The Hackbridge Cable Co. Ltd.* · W. T. Henley's Telegraph Works Co. Ltd. Johnson & Phillips Ltd · The Liverpool Electric Cable Co. Ltd · Metropolitan Electric Cable & Construction Co. Ltd · Pirelli-General Cable Works Ltd. (The General Electric Co. Ltd.) · St. Helens Cable & Rubber Co. Ltd. Siemens Edison Swan Ltd · Standard Telephones & Cables Ltd · The Telegraph Construction & Maintenance Co. Ltd.

** C.M.A. Trade Marks for Mains Cables only*

Insist on a cable with the C.M.A. label

The Roman Warrior and the letters 'C.M.A.' are British Registered Certification Trade Marks.

CABLE MAKERS ASSOCIATION

CABLE MAKERS ASSOCIATION, 52-54 HIGH HOLBORN, LONDON, W.C.1. TELEPHONE: HOLBORN 7633

CMA 23

BOLTON'S

HOLLOW COPPER CONDUCTORS

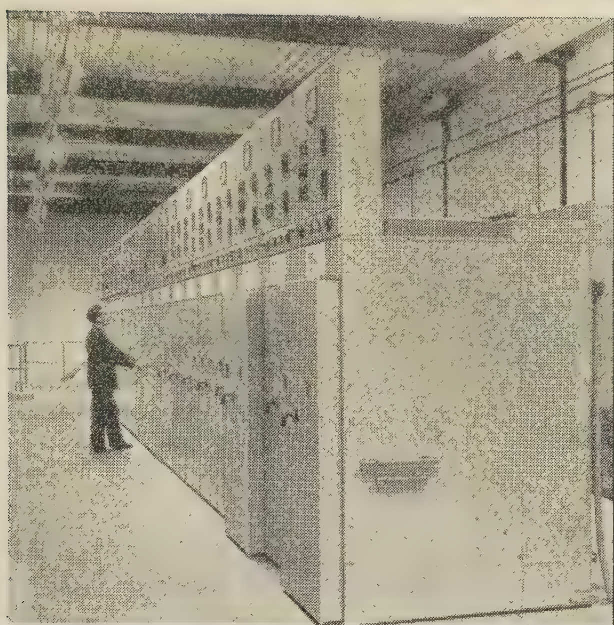
for rotor and stator windings of direct-cooled alternators and other electrical equipment. Made from H.C., "Combarloy", and other silver-bearing h.c. copper.

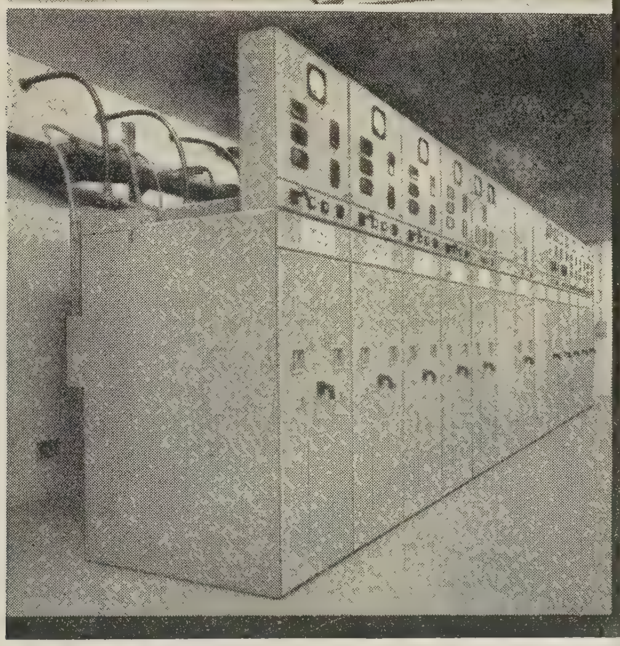
Your enquiries are invited, and the services of our Technical Staff are at your disposal.

175 YEARS SERVICE TO INDUSTRY

THOMAS BOLTON & SONS LTD

Head Office: Mersey Copper Works, Widnes, Lancs. Tel. Widnes 2022
London Office and Export Sales Dept.: 168 Regent Street, W.1. Telephone: REGent 6427. WORKS: STAFFORDSHIRE: Froghall and Oakamoor, Stoke-on-Trent. LANCASHIRE: Mersey Copper Works, Widnes; Sutton Rolling Mills, St. Helens.





THE STEEL COMPANY OF WALES

VELINDRE WORKS

The electrical distribution within the Velindre Works is controlled by Reyrolle 3·3-kV 150-MVA air-break circuit-breakers.

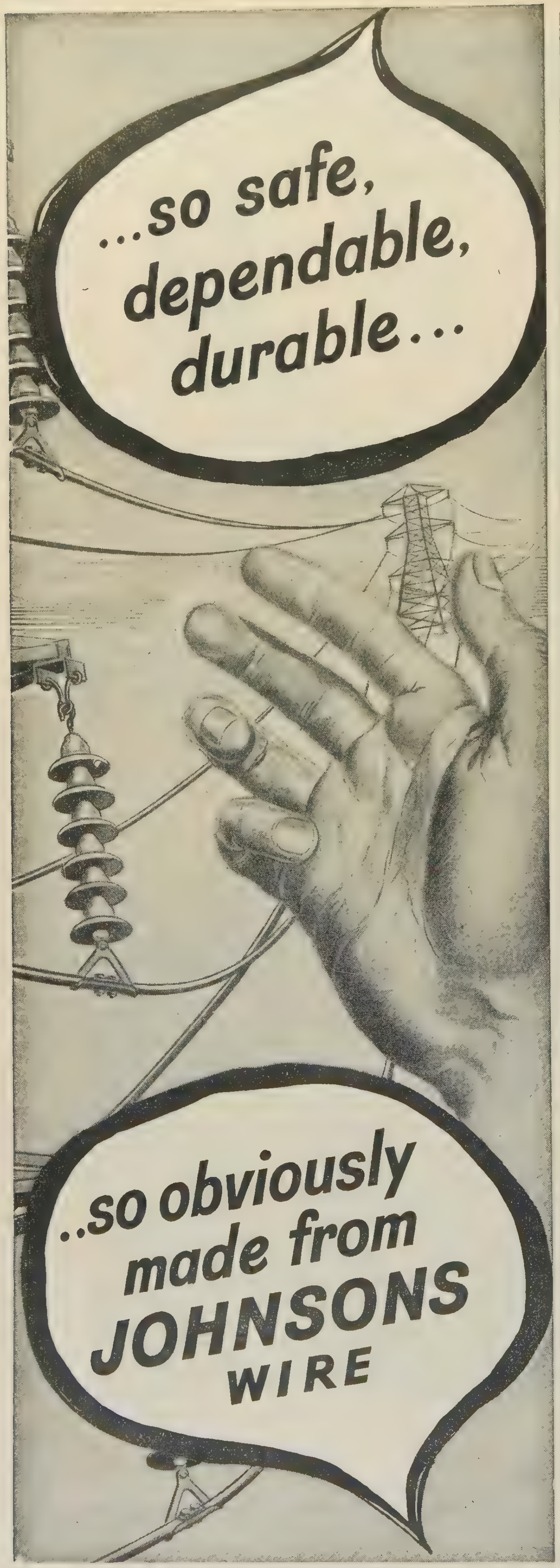
Reyrolle also supplied the 33-kV 1000-MVA outdoor small-oil-volume circuit-breakers controlling the incoming supply.

Photographs by courtesy of The Steel Company of Wales and the South Wales Electricity Board

CONSULTING ENGINEERS. McLELLAN & PARTNERS

Reyrolle

A. REYROLLE & CO. LTD • HEBBURN - COUNTY DURHAM - ENGLAND



RICHARD JOHNSON & NEPHEW LIMITED, MANCHESTER 11 Tel. EAST 1431

WRITE FOR BOOKLET ON THIS SUBJECT

ELIMINATE COMPOUND DRAINAGE...

....by using GLOVERS STANDARD PAPER INSULATED CABLES.... which are NON-DRAINING in any situation

GLOVERS STANDARD CABLES "for normal distribution work can be used for vertical installation without any special precautions being necessary..."

W. T. GLOVER & CO. LTD.
MEMBERS OF THE CMA
TRAFFORD PARK MANCHESTER 17
TRAFFORD PARK 2141

ZENITH
(REGD. TRADE-MARK)

Insulation
FLASH TEST EQUIPMENT
with the unique safety test prods

Equipped with "VARIAC" primary control giving continuous H.T. voltage regulation from zero to maximum. Standard outputs up to 2,000 volts and 3,000 volts.

Illustrated brochure free on request

The ZENITH ELECTRIC CO. LTD.
ZENITH WORKS, VILLIERS ROAD, WILLESDEN GREEN
LONDON, N.W.2

Telephone: WILlesden 6581-5 *Telegrams:* Voltaohm, Norphone, London

MANUFACTURERS OF ELECTRICAL EQUIPMENT
INCLUDING RADIO AND TELEVISION COMPONENTS

ON SERVICE IN OIL REFINERIES THROUGHOUT THE WORLD

M&C S

UNIT TYPE MOTOR STARTERS

For Service on Supplies up to 660 Volts

Contactor Starters .. up to 300 H.P.

Oil-Immersed Circuit-Breakers up to 1,600 Amp.

Busbar Section Switches up to 2,000 Amp.

H.R.C. Switch Fuse Units. Metering Units

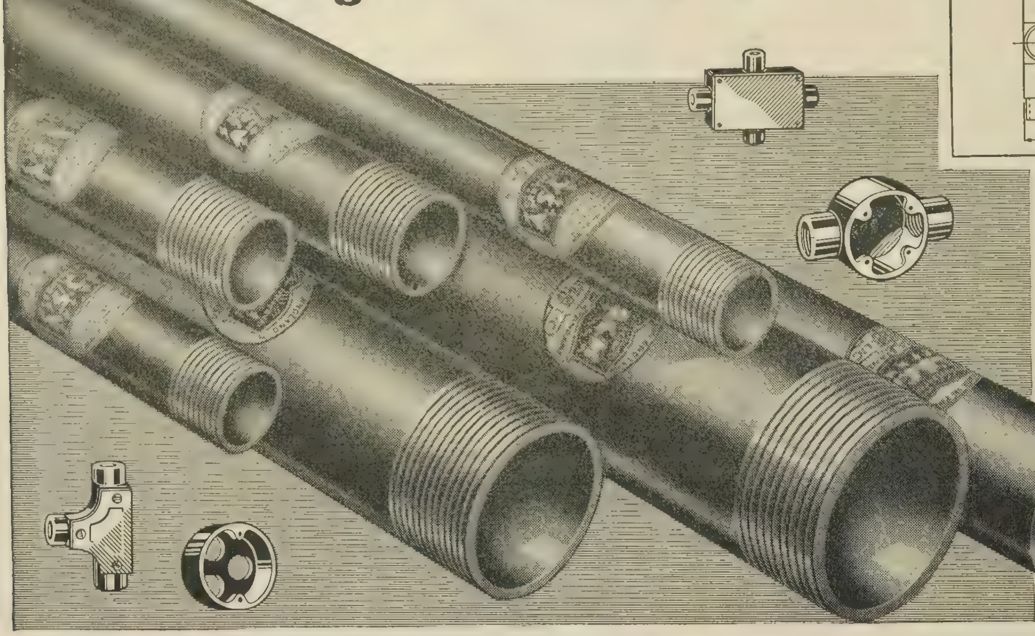
M&C S

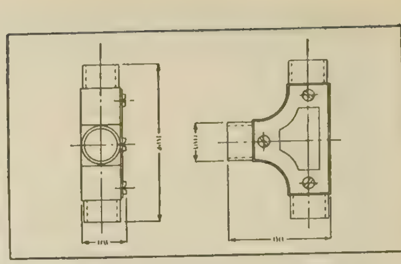
M. & C. SWITCHGEAR, LTD.

KIRKINTILLOCH, GLASGOW.

LONDON OFFICE, 36 VICTORIA ST., S.W.1. SHEFFIELD OFFICE, OLIVE GROVE RD.

Right from the first . . .





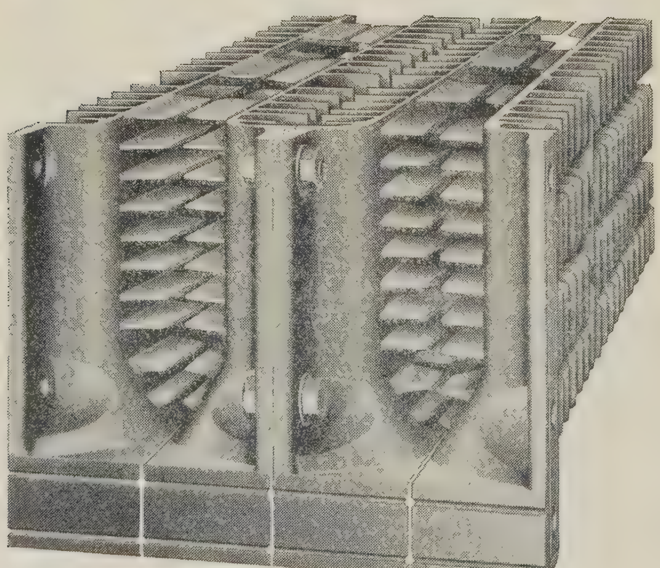
A job completed in METALLIC conduit is a job completed for good. METALLIC finishes ensure complete protection against corrosion, and will withstand bending without the slightest flaking. This durability, coupled with consistent accuracy, ensures easier installation and maintenance.

they're made to last . . . METALLIC CONDUIT TUBES & FITTINGS

A TI COMPANY

THE METALLIC SEAMLESS TUBE CO. LTD., LUDGATE HILL, BIRMINGHAM 3
ALSO AT LONDON, NEWCASTLE-ON-TYNE, LEEDS, SWANSEA & GLASGOW

NEW The KABLITZ-GREEN Cast Iron AIRHEATER



Cast iron, as has long been established, has remarkably good corrosion-resisting properties under the operating conditions of an airheater, and will give many times the life of steel constructions.

The Kablitz-Green Airheater, being of the plate-type with extended surfaces having slightly curved and staggered fins, gives high heat transfer rates with minimum loss of air and gas draught.

Installations are very compact. No driving mechanism is involved and there are no power costs. Cleaning can readily be done by any conventional system.

Further particulars available on request.

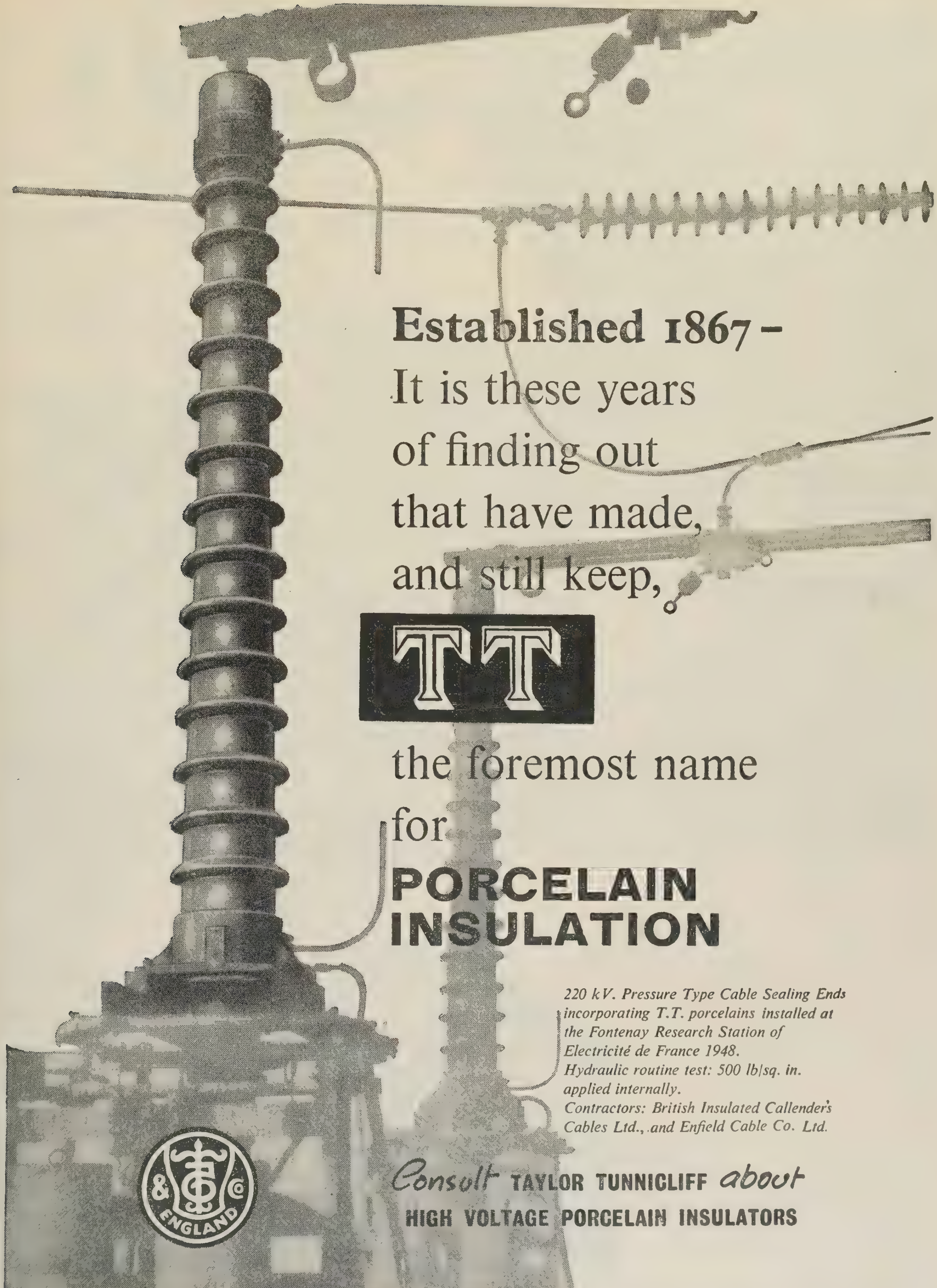
Manufactured by the makers of the world famous

GREEN'S ECONOMISER

E. GREEN & SON LTD · WAKEFIELD

Makers of economisers for more than one hundred years

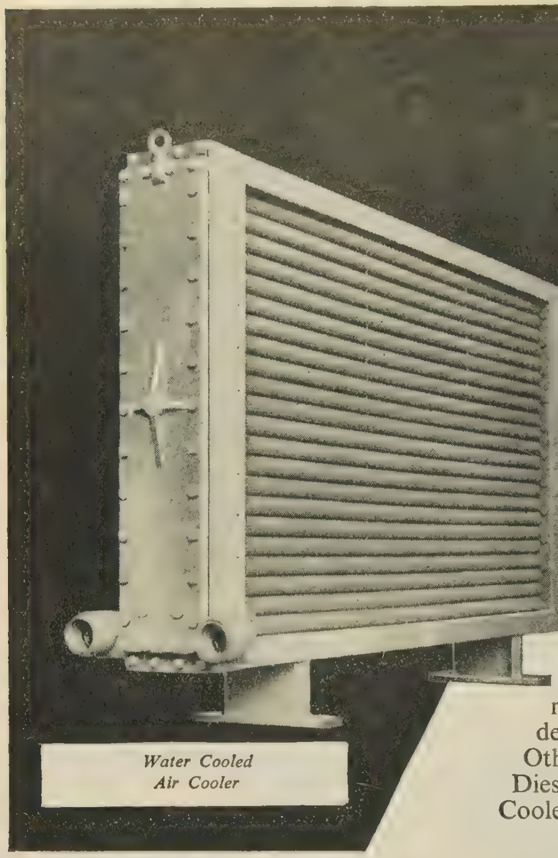
GE198



TAYLOR TUNNICLIFF & CO. LTD., Head Office: EASTWOOD · HANLEY · STOKE-ON-TRENT · STAFFORDSHIRE
Telephone: Stoke-on-Trent 25272-5. · London Office: 125 HIGH HOLBORN, W.C.1. Telephone: Holborn 1951-2

SPIRAL TUBE
COOLERS

for ALTERNATORS, MOTORS GENERATORS AND TRANSFORMERS

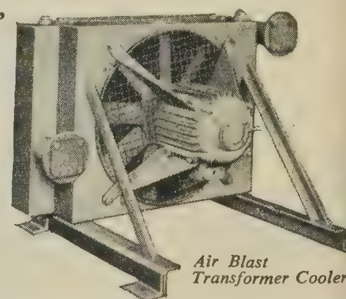

Water Cooled Air Cooler

Over many years the company's technicians have progressively developed special cooling equipment in conjunction with the Electrical Engineering Industry. The extensive knowledge gained thereby ensures the successful solution of all cooling problems.

For most installations either water-cooled or air-cooled equipment is used, the usual Alternator or Motor Cooler is water-cooled, whilst for Transformer Cooling both water and air-cooled designs are in use.

Each installation receives individual attention, and is designed to meet with requirements peculiar to the particular design and conditions.

Other products include Air Heaters, Diesel Engine Coolers, Compressed Air Coolers.


Air Blast Transformer Cooler

Write now for full details.

THE SPIRAL TUBE & COMPONENTS CO. LTD., OSMASTON PARK ROAD, DERBY. TELEPHONE: DERBY 48761 (3 lines)

London Office: Honeypot Lane, Stanmore, Middlesex. Telephone: Edgeware 4658/9

"Let's tackle this problem once and for all"
SAID THE CHAIRMAN

"We're agreed 'clean air' is here to stay but is this the best way to achieve it?"

"*It's not the cheapest—in terms of initial cost at any rate.*"

"But can we afford to settle for anything cheaper?"

"*Afford to? I don't quite follow you.*"

"I am thinking in terms of power costs, running costs and so on. You know how maintenance and repairs can run away with the money."

"*It still seems a high price to pay.*"

"Not for long years of trouble-free running. I suggest, gentlemen, that we tackle our 'clean air' problem once and for all with electro-precipitation—by Simon-Carves of course."

High efficiency electro-precipitation by **Simon-Carves Ltd**

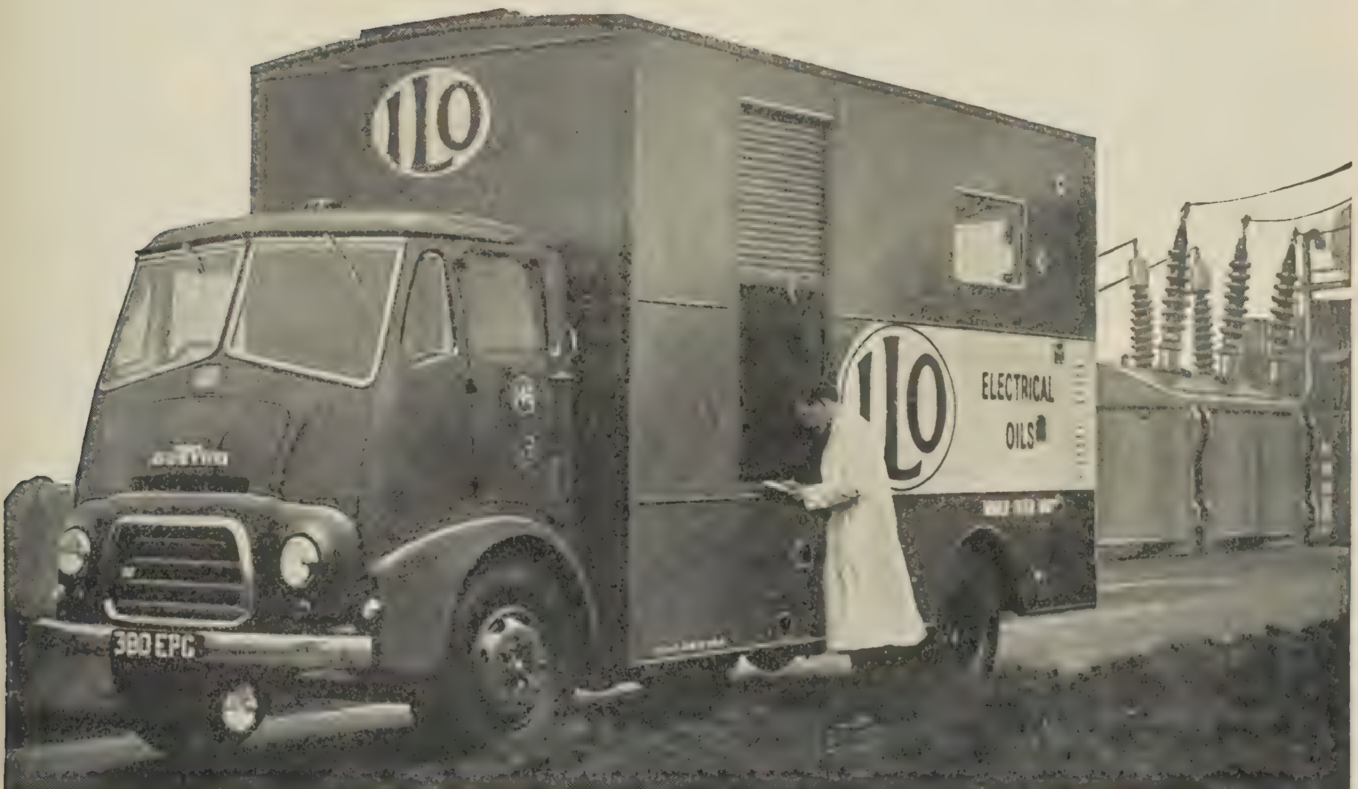
STOCKPORT, ENGLAND

SIMON ENGINEERING GROUP

OVERSEAS COMPANIES | *Simon-Carves (Africa) (Pty) Ltd : Johannesburg* *Simon-Carves (Australia) Pty Ltd : Botany, N.S.W.*

SC.201

ILO service to transformer oil users



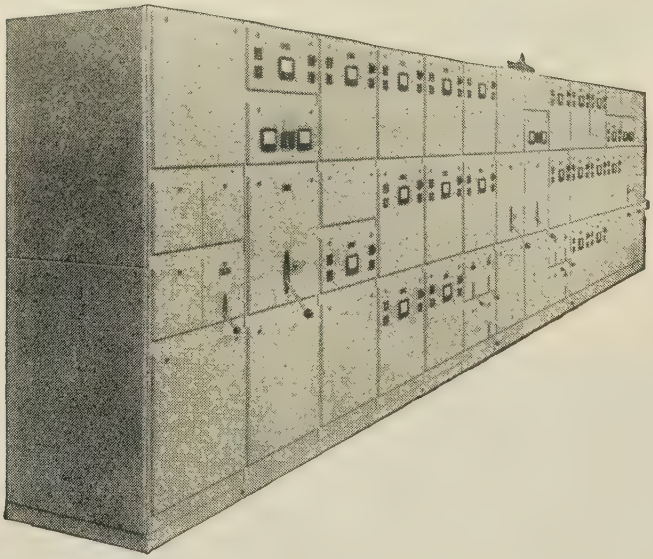
When you use ILO Electrical Oil, you benefit in three ways—from a product which maintains consistently high quality, from the advice of experienced technicians and from such facilities as this self powered, 1000 gallon/hour Mobile Filter Unit, for the treatment of degraded oil on site.

ILO ELECTRICAL OILS

WAKEFIELD-DICK INDUSTRIAL OILS LTD., 67 Grosvenor Street, London, W.1. GROsvenor 6050

Member of the worldwide Wakefield Castrol Organisation

GROUPED MOTOR CONTROL CENTRES



Patent No. 783957

FOR INSTALLING INDOORS OR OUTDOORS IN ANY CLIMATE, ANYWHERE

A NOTEWORTHY FEATURE OF OUR DESIGN IS THE PATENTED "LIFT-OFF-DOOR" CARRYING THE CONTROL EQUIPMENT AND DISPENSING WITH ALL TRAILING CABLES AND WIRES

FULLY SHROUDED PLUG-IN CONTACTS ENSURE MAXIMUM SAFETY AND FLEXIBILITY

ELECTRO MECHANICAL MFG. CO. LTD.

Subsidiary of Yorkshire Switchgear and Engineering Co. Ltd., Leeds

Head Office and Works: MARLBOROUGH STREET, SCARBOROUGH. Telephone: SCARBOROUGH 2715-6

London Office and Showroom: GRAND BUILDINGS, TRAFALGAR SQUARE, W.C.2. Telephone: Whitehall 3530

THE JOURNAL OF

The British Nuclear Energy Conference

The Institution of Civil Engineers
The Institution of Mechanical Engineers
The Institution of Electrical Engineers
The Institute of Physics
The Institution of Chemical Engineers
The Institute of Metals
The Iron and Steel Institute
The Institute of Fuel
The Joint Panel on Nuclear Marine Propulsion

PUBLISHED JANUARY, APRIL, JULY, OCTOBER

The Journal contains papers and discussions on the applications of nuclear energy and ancillary subjects

ANNUAL SUBSCRIPTIONS:

MEMBERS 30/– post free

NON-MEMBERS 60/– post free

Full particulars are available from

The Secretary • B.N.E.C. • 1-7 Great George Street • London • SW1

HACKBRIDGE AND HEWITTIC ELECTRIC Co LTD

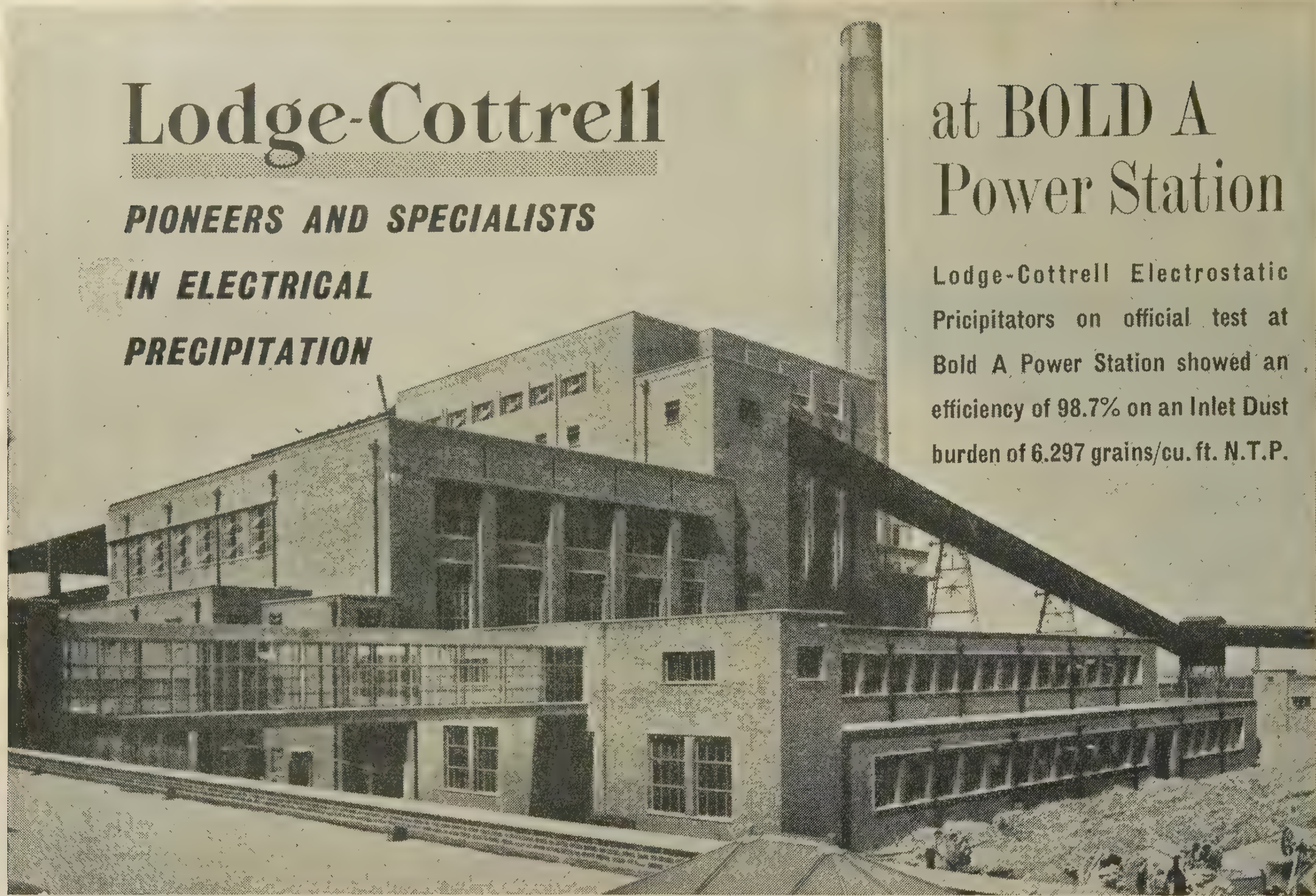
HACKBRIDGE TRANSFORMERS

HACKBRIDGE AND HEWITTIC ELECTRIC COMPANY LTD

HERSHAM · WALTON-ON-THAMES · SURREY

Telephone: Walton-on-Thames 760 (8 lines) *Telegrams & Cables: "Electric, Walton-on-Thames"*

VERSEAS REPRESENTATIVES: ARGENTINA: H. A. Roberts & Cia., S.R.L., Buenos Aires. AUSTRALIA: Hackbridge and Hewittic Electric Co. Ltd., 171, Fitzroy treet, St. Kilda, Victoria; N.S.W.: Queensland: W. Australia: Elder, Smith & Co. Ltd.; South Australia: Parsons & Robertson Ltd.; Tasmania: H. M. Bamford & Sons Pty.) Ltd., Hobart. BELGIUM & LUXEMBOURG: Pierre Pollie, Brussels 3. BRAZIL: Oscar G. Mors, Sao Paulo. BURMA: Neonlite Manufacturing & Trading o. Ltd., Rangoon. CANADA: Hackbridge and Hewittic Electric Co. of Canada Ltd., Montreal; The Northern Electric Co. Ltd., Montreal, etc. CEYLON: Envee Ess Ltd., Colombo. CHILE: Sociedad Importadora del Pacifico Ltda., Santiago. EAST AFRICA: Gerald Hoe & Co., Nairobi. EGYPT: Giacomo Cohenca Fils, S.A.E., airo. FINLAND: Sahko-ja Koneliike O.Y. Hermes, Helsinki. GHANA, NIGERIA & SIERRA LEONE: Glyndova Ltd. GREECE: Charilaos C. Coroneos, Athens. NDIA: Steam & Mining Equipment (India) Private Ltd., Calcutta; Easun Engineering Co. Ltd., Madras 1. IRAQ: J. P. Bahoshy Bros., Baghdad. MALAYA, INGAPORE & BORNEO: Harper, Gilfillan & Co. Ltd., Kuala Lumpur. NETHERLANDS: J. Kater E.I., Ouderkerk a.d. Amstel. NEW ZEALAND: Richardson, McCabe & Co. Ltd., Wellington, etc. PAKISTAN: The Karachi Radio Co., Karachi 3. SOUTH AFRICA: Arthur Trevor Williams (Pty. Ltd., Johannesburg, etc. ENTRAL AFRICAN FEDERATION: Arthur Trevor Williams (Pty.) Ltd., Salisbury. THAILAND: Vichien Phanich Co. Ltd., Bangkok. TRINIDAD & TOBAGO: Thomas Peake & Co., Port of Spain. TURKEY: Dr. H. Salim Öker, Ankara. U.S.A.: Hackbridge and Hewittic Electric Co. Ltd., P.O. Box 234, Pittsburgh 30, Pennsylvania. VENEZUELA: Oficina de Ingenieria Sociedad Anonima, Caracas.



LODGE-COTTRELL LIMITED GEORGE ST PARADE BIRMINGHAM *Tel: Central 7714* LONDON *Central 5488*

THE PROCEEDINGS OF THE
INSTITUTION OF ELECTRICAL ENGINEERS

TEN YEAR INDEX

1942—1951

A TEN-YEAR INDEX to the *Journal of The Institution of Electrical Engineers* for the years 1942–48 and the *Proceedings* 1949–51 (vol. 89–98) can be obtained on application to the Secretary.

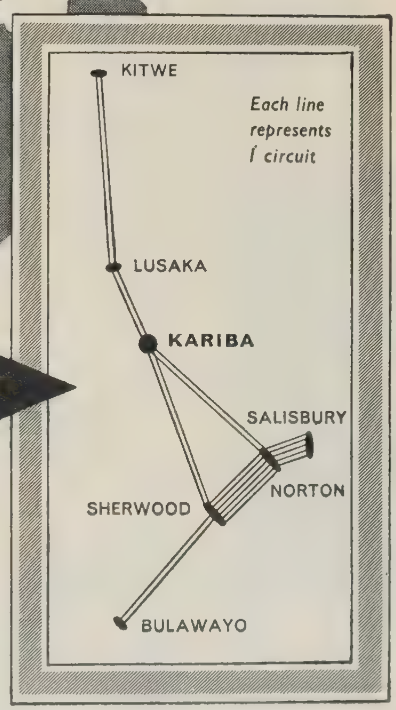
The published price is £1 5s. 0d. (post free), but any member of The Institution may have a copy at the reduced price of £1 (post free).

Phenomenal Projects
DEMAND
Faultless Communications

G.E.C.

POWER LINE CARRIER EQUIPMENT
FOR THE
KARIBA HYDRO-ELECTRIC PROJECT

The Power Line Carrier Equipment to be used in the KARIBA Hydro-electric Project has been designed and manufactured throughout by The General Electric Company for Standard Telephones and Cables Ltd., the main telecommunication contractors for the project. The equipment will provide the communications facilities over the 330 kV network that radiates from Kariba and is controlled from Sherwood. The main feeders from Kariba to Kitwe, Sherwood and Norton are 267, 200 and 159 miles long, respectively. Other feeders link the supply network to Bulawayo and Salisbury. This is but one of the many major power projects with which the Company has been associated throughout its many years of service to Industry.

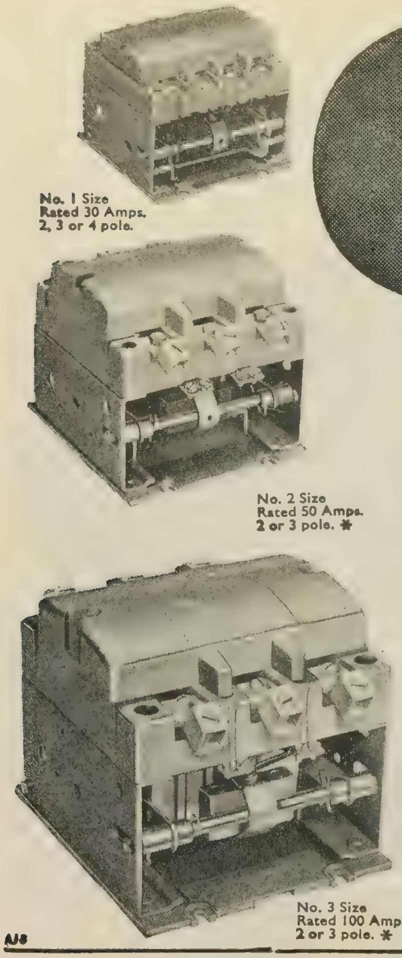


G.E.C.

Everything for Telecommunications:—

THE GENERAL ELECTRIC COMPANY LIMITED OF ENGLAND TELEPHONE, RADIO AND TELEVISION WORKS, COVENTRY

G.E.C 16



Contactors

INCORPORATING THE ARROW EXCLUSIVE 'RIGHT-ANGLE' MECHANISM.

THE SMALLEST CONTACTORS FOR THEIR RATINGS.

ALL RATINGS AT 550v A.C. PER POLE.

AUXILIARY SWITCHES AVAILABLE, N/O, N/C or N/O-N/C.

ALL TYPES CAN BE SUPPLIED AS INTERLOCKED UNITS.

CONFORMING TO NEMA SIZES 1, 2 & 3.

TO B.S.S. 775 (Revised). C.S.A. APPROVED.

* 4 & 5 pole versions also supplied.

LATEST! our new 15 amp direct acting contactor

Make sure you get full information about the finest contactors made today—free on request from

ARROW ELECTRIC SWITCHES LTD
HANGER LANE · LONDON · W.5.

ARROW

CHAMBERLAIN & HOOKHAM
TYPE P

PROCESS TIMERS

FOR ACCURATE AND AUTOMATIC PROCESS CONTROL

- ★ Scale ranges from 0–10 secs. up to 24 hours.
- ★ Settings down to 1/10 sec.
- ★ Accuracy within 0·25% of full scale range.
- ★ Available as single units or self-mounting or as complete control panels.
- ★ Any operation requiring time control by electrical means can be regulated by this instrument.

Chamberlain and Hookham

CHAMBERLAIN & HOOKHAM LTD.
BIRMINGHAM

TYPE P PROCESS TIMER
CAT. SECTION 11300

THE INSTITUTION OF ELECTRICAL ENGINEERS

presents

THE INQUIRING MIND

A film outlining the opportunities for a career in the field of electrical engineering

Producer: Oswald Skilbeck *Director: Seafield Head*
Commentator: Edward Chapman

Copies of the film may be obtained on loan by schools and other organizations for showing to audiences of boys and girls interested in a professional career in electrical engineering. The film is available in either 35mm or 16mm sound, and the running time is 30 min.

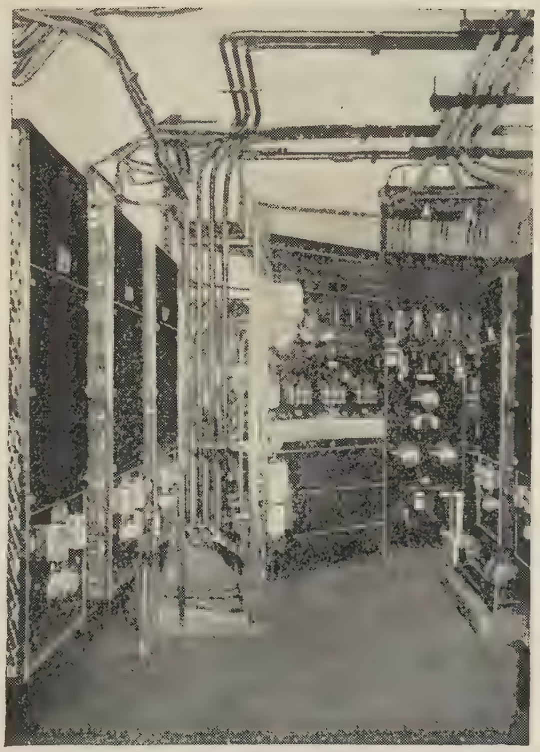
Application should be made to

THE SECRETARY
THE INSTITUTION OF ELECTRICAL ENGINEERS
SAVOY PLACE, LONDON, W.C.2

WESTINGHOUSE

EXPERIENCE

is your Guarantee for all Rectifier problems



1932 *A group of copper-oxide chargers were installed at Selfridges Ltd., for road delivery vehicles.*

1957 *Westalite battery chargers replaced the copper-oxide types at Selfridges Ltd.*

WESTINGHOUSE BRAKE AND SIGNAL CO. LTD., 82 YORK WAY, KING'S CROSS, LONDON, N.1
Telephone: TERminus 6432

Publications of

THE INSTITUTION OF ELECTRICAL ENGINEERS

Journal of The Institution—Monthly

Proceedings of The Institution

PART A (Power Engineering)—Alternate Months
PART B (Radio and Electronic Engineering—including Communication Engineering)—Alternate Months
PART C (Institution Monographs)—In collected form twice a year

Special Issues

VOL. 94 (1947) PART IIA (Convention on Automatic Regulators and Servomechanisms)
VOL. 94 (1947) PART IIIA (Convention on Radiocommunication)
VOL. 97 (1950) PART IA (Convention on Electric Railway Traction)
VOL. 99 (1952) PART IIIA (Convention on the British Contribution to Television)
VOL. 100 (1953) PART IIA (Symposium of Papers on Insulating Materials)
Heaviside Centenary Volume (1950)
Thermionic Valves: the First 50 years (1955)
VOL. 103 (1956) PART B SUPPLEMENTS 1-3 (Convention on Digital-Computer Techniques)
VOL. 103 (1956) PART A Supplement 1 (Convention on Electrical Equipment for Aircraft)
VOL. 104 (1957) PART B SUPPLEMENT 4 (Symposium on the Transatlantic Telephone Cable)
VOL. 104 (1957) PART B SUPPLEMENTS 5-7 (Convention on Ferrites)
VOL. 105 (1958) PART B Supplement 8 (Symposium on Long Distance Propagation above 30 Mc/s)
VOL. 105 (1958) PART B Supplement 9 (Convention on Radio Aids to Aeronautical and Marine Navigation)

★

PROCEEDINGS - *Paper and Reprint Service*

PAPERS READ AT MEETINGS

Papers accepted for reading at Institution meetings and subsequent republication in the *Proceedings* are published individually without delay, free of charge. Titles are announced in the *Journal* of The Institution, and abstracts are published in *Science Abstracts*.

REPRINTS

After publication in the *Proceedings* all Papers are available as Reprints, price 2s. (post free). The Reprint contains the text of the Paper in its final form, together with the Discussion, if any. Those who obtain a copy of a Paper published individually—if they do not take the Part of the *Proceedings* in which it will be republished—are urged to apply in due course for a Reprint, as this is the final and correct version.

CONVENTION PAPERS

Papers accepted for presentation at a Convention or Symposium, and subsequent republication as a Supplement to the appropriate part of the *Proceedings*, are published shortly before the Convention, but are usually available only in sets. No Reprints are available.

MONOGRAPHS

Institution Monographs (on subjects of importance to a limited number of readers) are available separately, price 2s. (post free). Titles are announced in the *Journal* and abstracts are published in *Science Abstracts*. The Monographs are collected together and republished twice a year as Part C of the *Proceedings*.

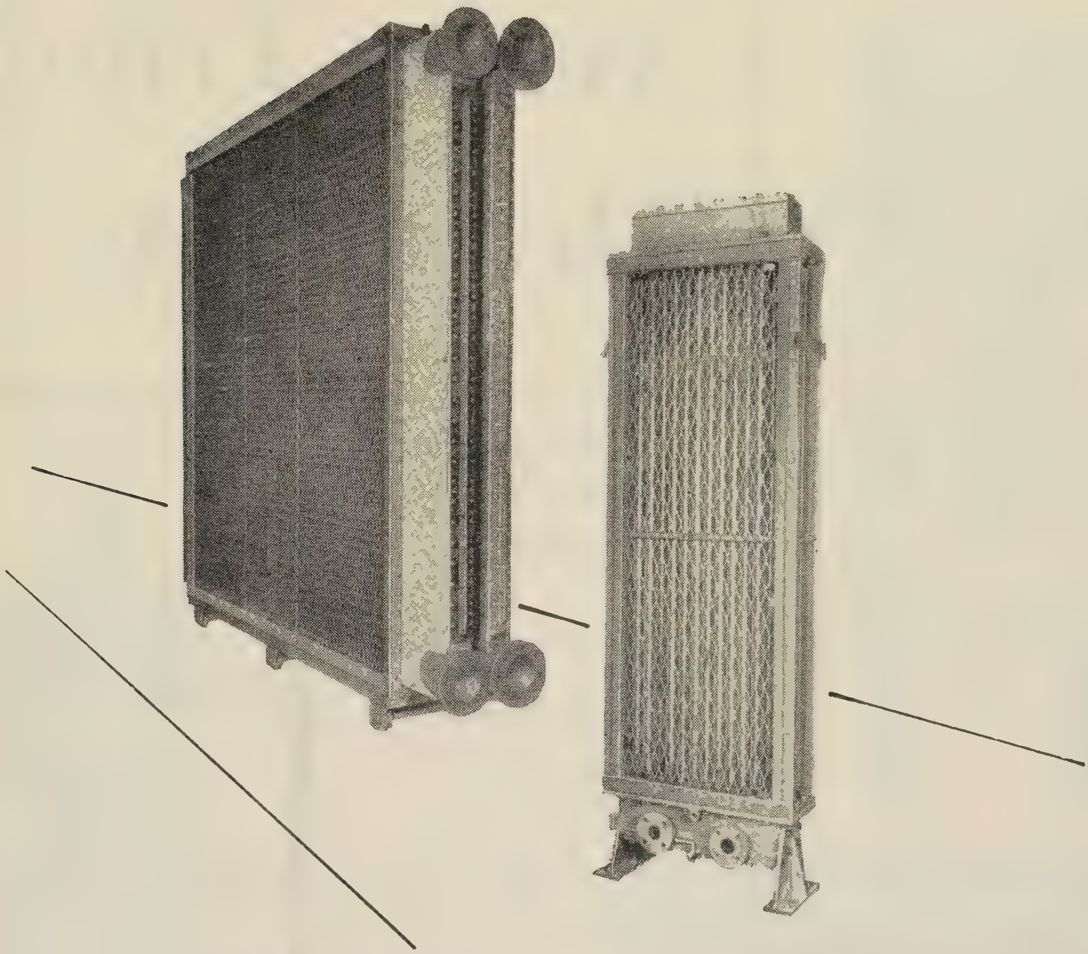
An application for a Paper, Reprint or Monograph should quote the author's name and the serial number of the Paper or Monograph, and should be accompanied by a remittance where appropriate. For convenience in making payments, books of five vouchers, price 10s., can be supplied.

SCIENCE ABSTRACTS

Published monthly in two sections
SECTION A: Physics
SECTION B: Electrical Engineering

Prices of the above publications on application to the Secretary of The Institution, Savoy Place, W.C.2.

HEENAN



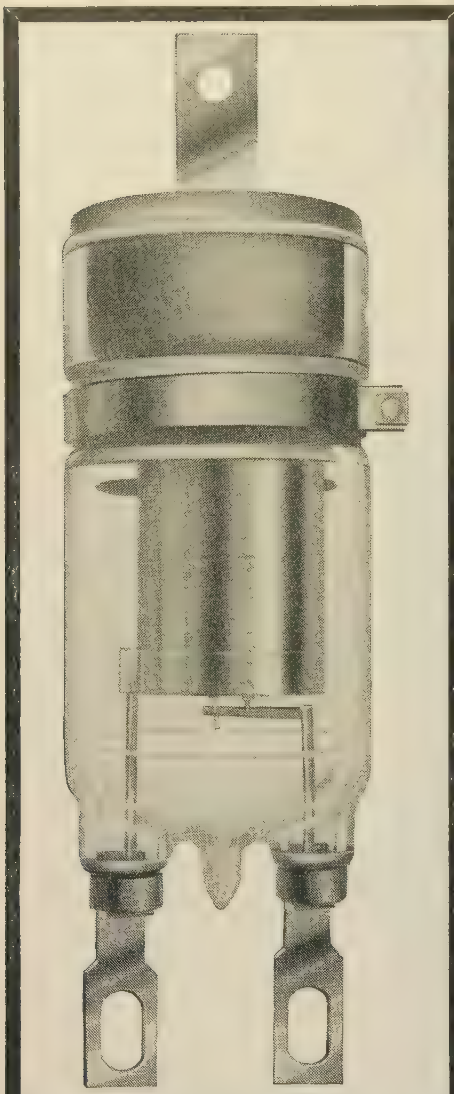
CLOSED CIRCUIT

AIR

COOLERS

Lengthy experience in practical design
Wide variety of ducting and damper layouts
Highly efficient cooling surfaces
Heavy and robust construction
Special attention to ease of access and maintenance

HEENAN & FROUDE LIMITED • WORCESTER • ENGLAND

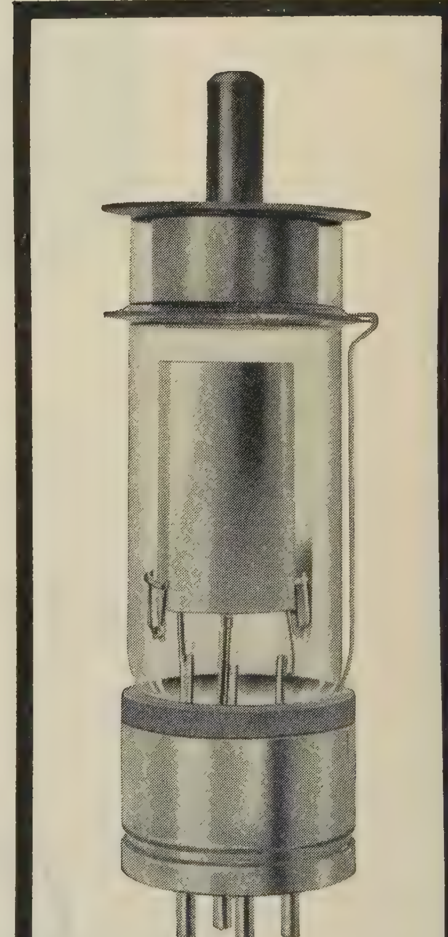


XR1-12

6 and 12 amp Xenon Triode Thyratrons

New Disc-Seal construction gives these positive advantages

- **High hold-off voltage**
- **Freedom from arc-back**
- **Ruggedness**
- **Long life**
- **A year's guarantee**



XR1-6400A

The basic advantages of Xenon thyratrons are enhanced in the Mullard XR1-6400A and XR1-12 by a new type of construction which provides improved electrical and mechanical performance.

The XR1-12 will continuously control currents of up to 12 amps, while the maximum capacity of the XR1-6400A is 6.4 amps. These two valves are rugged and their long life is backed by a year's guarantee.

Their heating-up time is only one minute and they will operate efficiently over a wide range of ambient temperatures.

Both types can be employed with confidence in a variety of power control applications including direct welding control, lighting control, motor control, electronic switches and regulated power supplies. Write to the address below for full data.

Type No.	American Type No.	Vf (V)	If (A)	va(pk) max. (kV)	P.I.V. max. (kV)	ik (pk) max. (A)	ik (av.) max. (A)	Heating-up time (secs)
XR1–6400A	6807	2.5	21	1.5	1.5	80	6.4	60
XR1–12	5855	2.5	34	1.5	1.5	150	12.5	60

Mullard

GOVERNMENT AND INDUSTRIAL VALVE DIVISION

Mullard Limited
Mullard House · Torrington Place · London W.C.1 Tel. LANgham 6633

MVT333c

INDEX OF ADVERTISERS

Portable Power with "RUNTACT"

DONOVAN'S

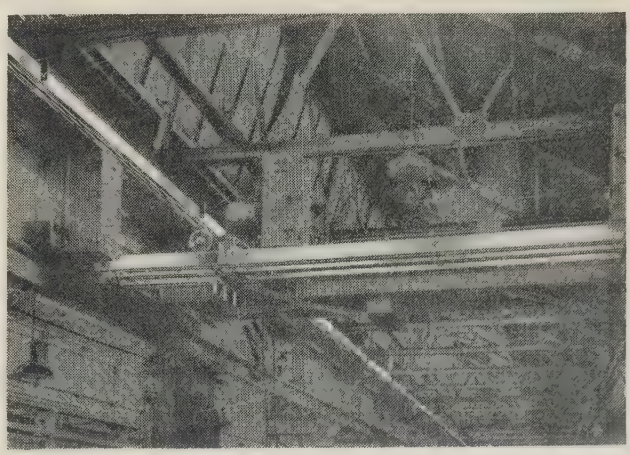
OVERHEAD BUS-BAR EQUIPMENT
TRAVELLING CONTACT TYPE

Donovan "Runtact" power duct is ideally suitable for feeding electric power to hoists or small cranes, and enables portable power to be supplied over long lengths with the utmost facility. Other applications are Moving Test Lines, Production and Assembly Lines, and Portable Tools. Outstanding features include:

- Enclosed conductors which eliminate hazards of exposed wiring.
- Standard straight or curved sections which can be applied to most installations.
- Adaptable to existing as well as new installations.

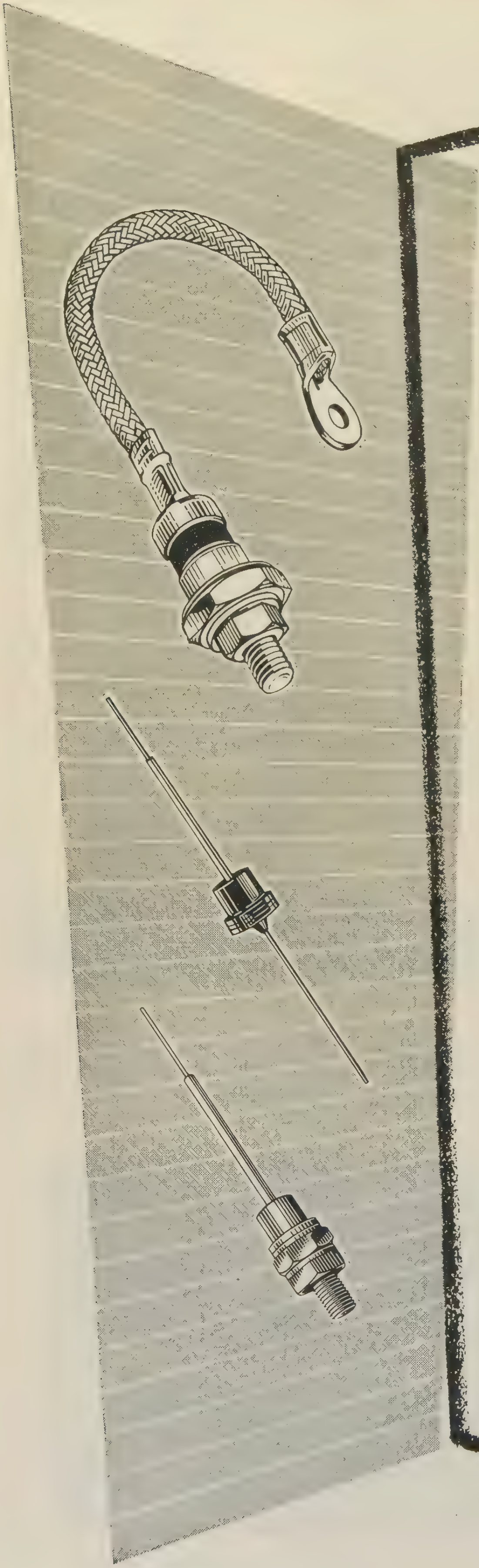
Further details on application.

Illustrated is an installation fitted to a 2-ton crane manufactured by AaBACas Engineering Co Ltd.



THE DONOVAN ELECTRICAL CO LTD
GRANVILLE STREET · BIRMINGHAM I.

LONDON DEPOT: 149-151 YORK WAY, N.7
GLASGOW DEPOT: 22 PITT ST. C.2
Sales Engineers available in—
LONDON, BIRMINGHAM, BELFAST, MANCHESTER, GLASGOW, BOURNEMOUTH.



FERRANTI

DIFFUSED JUNCTION POWER RECTIFIERS

Ferranti offer a range of hermetically sealed rectifiers with peak inverse voltage ratings up to 300 volts, and rectified current from **100 mA. to 30 amps.** from a single convection cooled diode.

SPECIAL FEATURES

- More power in smaller space.
- High AC to DC conversion efficiency.
- Excellent regulation.
- Reliable operation at high temperature.
- Minimum maintenance.
- High forward and very low reverse current.

Ferranti Silicon Rectifiers are rigorously tested to Service and Industrial Specifications covering vibration, shock and humidity, and are suitable for Airborne, Marine and Industrial Electrical applications.

Data Sheets and Application Reports are available and will be supplied on request.

FERRANTI

FERRANTI LTD · GEM MILL · CHADDERTON · OLDHAM · LANCASHIRE

London Office: KERN HOUSE, 36 KINGSWAY, W.C.2.

FE185/2

The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.
An example of the preferred form of bibliographical references will be found beneath the list of contents.

THE PROCEEDINGS OF
THE INSTITUTION OF ELECTRICAL ENGINEERS

EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

VOL. 105. PART A. No. 24. DECEMBER 1958

621.387: 621.316.57

The Institution of Electrical Engineers
Paper No. 2723 M
Dec. 1958
©

HIGH-TEMPERATURE EFFECTS ON FLASHOVER IN AIR

By L. L. ALSTON, B.Sc.(Eng.), Ph.D., Associate Member.

(*The paper was first received* 13*th January, and in revised form* 1*st July*, 1958.)

SUMMARY

Paschen's law has been confirmed experimentally for millimetric gaps at temperatures up to 1 100° C, and the flashover voltages obtained were independent of electrode material.

The effect of electrode hot spots at temperatures up to 1 200° C was investigated in different electric fields, the bulk of the test gap being at room temperature. Under uniform-field conditions, hot spots caused a substantial lowering of flashover voltage, but their effect decreased with increase in the divergence of the field. A hot spot in the region of least electric stress had no significant effect when the ratio of maximum to minimum stress exceeded a value of the order of, but greater than, the ratio of hot spot to ambient temperature.

Evidence is advanced in support of the view that the operation of Trigatron gaps can be explained in terms of hot-spot formation.

(1) INTRODUCTION

In comparison with the research devoted to other aspects of flashover phenomena, relatively little attention has been given to the effects of high temperatures. Nevertheless, these can be of considerable importance, for example in circuit-breakers, where hot gases produced during arcing weaken the electric strength between contacts, and on being exhausted may affect the external flashover of the circuit-breaker. Furthermore, hot spots caused by arc roots may remain on electrodes after most of the gas has been cooled or replaced, and their effect needs to be assessed. Similar considerations apply to studies of the dielectric recovery of air-gaps, and temperature effects have been used to explain the operation of triggered spark-gaps such as the Trigatron. Again, a trend exists for an increase in the temperature rating of electrical machinery, and this may apply to high-voltage equipment in which air is used for electrical insulation.

Temperature studies have previously been carried out by Bowker[1] up to 860° C, for hydrogen and nitrogen between copper and nickel spheres. The electric field and temperature were uniform throughout the gap, and Paschen's law was found to hold. Frank[2] undertook similar work with steel spheres in air, but his data agreed with Paschen's law only up to about 400° C. At higher temperatures he recorded an undue lowering of flashover voltage, which he ascribed to thermionic emission. Bowker[1] considered this deviation from Paschen's law to be due to effects such as oxidation and roughening of the electrode surface, and advanced a further criticism that the data[2] did not agree with standard sphere-gap calibrations. In view of these differences, further verification of Paschen's law was required at high temperatures, and this constituted one object of the present investigation.

In the course of a study of triggered spark-gaps, Broadbent and Wood[3] carried out experiments on flashover between 15 cm spheres, one of which had been drilled for the insertion of an electrically heated wire. In fact, this constituted a hot spot; flashover voltage decreased greatly with increase in temperature, and these results supported the view that the operation of Trigatron spark-gaps depended largely on the creation of a hot spot by the trigger discharge.

In Broadbent and Wood's experiments the gap spacing did not exceed 10 cm, i.e. it was less than the sphere diameter, and more divergent fields may occur in electrical equipment. A second object of the present work was to determine the effect of hot spots under conditions likely to occur in circuit-breakers, and these conditions were considered to be covered adequately by the following: a uniform electric field, a range of non-uniform fields with the hot spot in the region of least electric stress, and again with the hot spot in the region of highest stress.

(2) VERIFICATION OF PASCHEN'S LAW

An electrically heated furnace having a 2 in bore muffle open to the atmosphere at both ends was used to produce temperatures up to 1 100° C. These were measured on a platinum/platinum-rhodium thermocouple and were uniform to within 1% in the inter-electrode region.

The electrodes consisted of 1 cm discs with rounded edges, and were held with the flat faces parallel at the end of 1 cm diameter alumina tubes situated axially in the muffle. Copper, Elkonite (tungsten-copper) and Nimonic (nickel-chromium) electrodes were used at temperatures up to 900, 850 and 1 100° C,

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Dr. Alston is with A. Reyrolle and Co. Ltd.

© 1958: The Institution of Electrical Engineers.

respectively; gap spacings of 0·5, 1·0 and 2·0 mm were used for all materials, and also 2·5 and 3·0 mm for Nimonic alone. All test runs were started with unoxidized electrodes, and voltages were measured at progressively higher temperatures, i.e. the electrode temperature was not allowed to fall during a test run. This was done to restrict surface roughening due to heating and cooling.

Direct voltages, smoothed to 0·1%, were applied and were measured on a resistance-type voltmeter. Voltage was raised in steps of 5% maintained for a minute, unless flashover occurred earlier. Five flashovers were applied to determine one voltage value. The mean current through the test gap was measured at voltages below breakdown, and up to about 600° C it was less than 10^{-7} amp. A general increase of current with temperature was recorded at higher temperatures, and the maximum values obtained were of the order of 10^{-5} amp.

Results from one experiment are given in Fig. 1, where the

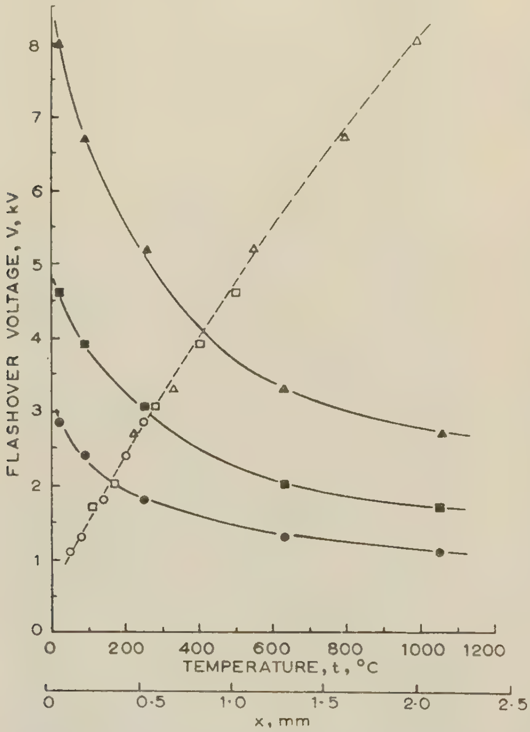


Fig. 1.—Flashover characteristics for 0·5–2·0 mm gaps at temperatures up to 1 100° C and atmospheric pressure: Nimonic electrodes.

Symbol		Gap, mm
(t, V)	(x, V)	
▲	△	2
■	□	1
●	○	0·5

$$x = \frac{293}{273 + t} \frac{P}{760} d \text{ millimetres}$$

flashover voltage, V, was first plotted to a base of temperature, t (full curves), and then replotted (dotted curve) as a function of a parameter, x, which is proportional to the product of gas density and gap spacing. It will be seen that the points which gave the three voltage/temperature curves resulted in only one V/x curve.

Two such experiments were carried out for each electrode material, and when the flashover voltages had been plotted on the same graph to a base of x it was found that all points lay close to the curve $V = 2 \cdot 54x + 2 \cdot 10\sqrt{x}$, V being in kilovolts and x in millimetres. The constants for this equation were calculated using the method suggested by Bruce;[4] compared to this equation, the values obtained by experiment for the flashover voltage, V, had a standard deviation of 5% and a maximum deviation of 12%. No correlation could be detected between the deviation of points and the electrode material or spacing, so that the scatter was taken to be due to experimental factors, such as distortion of the electrode assembly under the influence of heat, or variations in electrode profiles (for any pair of electrodes, voltages obtained at a given value of x were within ± 3% of their mean). Consequently flashover voltage is a function of x alone, and hence of the product of air density and gap spacing. This confirms Paschen's law.

The conclusions of the present work, that, in an approximately uniform field, flashover voltage is independent of electrode material and can be expressed in the form $V = Ax + B\sqrt{x}$, agree with observations from experiments in which the flashover voltage was varied principally by means of the spacing, the temperature and pressure being atmospheric. The term $B\sqrt{x}$ decreases in importance with increase in x, and to a first approximation $V \simeq Cx = K/T$, where C and K are constants and T is the absolute temperature. Consequently, to a first approximation, the electric strength of air is inversely proportional to the absolute temperature.

(3) THE EFFECT OF HOT SPOTS

Hot-spot effects were studied on sphere-plane gaps; the field configuration was varied usually by means of the gap spacing and occasionally by the sphere diameter, which was 2·5 cm unless otherwise stated. The hot spot was obtained by drilling a 0·32 cm hole in one of the electrodes and inserting through the hole the apex of a V-shaped 0·061 cm diameter Nichrome wire. The inner part of the apex was flush with the electrode surface so that the wire extended by its own thickness into the inter-electrode space: preliminary experiments indicated that, in this condition, the hot spot was more effective than if the wire did not extend into the inter-electrode region. The jutting out of the wire was intended to simulate the roughening of the electrode surface due to arcing, and furthermore it was preferred that flashover voltages obtained by experiment should be low (pessimistic) rather than the contrary.

The wire was heated through a specially insulated transformer and temperatures were measured optically above 700° C, and from the melting-points of chemicals at lower values. Except where otherwise stated, direct current was used for flashover to observe polarity effects. The spherical electrode was situated vertically above the plate, and confirmatory experiments showed that reversing this arrangement had no significant effect on the flashover voltage.

The hot-spot construction distorted the electric field in its immediate vicinity, so that, even in the absence of heating, the flashover voltage differed somewhat from the value obtained for normal sphere-plane gaps. A test run (using a 2·5 cm sphere) showed that when the hot-spot construction was in the plate this difference was less than 15% for a 0·5 cm gap and decreased rapidly with increase in spacing, being insignificant (less than 1%) above 2 cm. When the construction was in the sphere, its effect was more marked but flashover voltages were within 20% of those obtained in its absence.

The effects of hot spots will be discussed in terms of 'percentage flashover voltage' (p.f.v.), which is defined as the flashover voltage obtained with a given hot spot, expressed as a percentage of the flashover voltage obtained when the hot-spot temperature

is reduced to ambient. The ratio of hot-spot temperature to ambient temperature, both measured on the absolute scale, will be known as the 'temperature ratio', and the ratio of maximum to minimum stress in the gap will be known as the 'stress ratio'. Where values of the stress ratio are given, these have been obtained from the geometry of the electrodes,[5] and field distortion due to the hot-spot construction, and to space charges, has been ignored.

Several test runs were taken for every graph, and considerable scatter of results was observed when the electric field approached uniformity. This indicates that hot-spot effects in a specified gap cannot be fully defined in terms of hot-spot temperature alone, though such a definition is adequate for the present purpose. The hot spot, whether caused by arcing or otherwise, usually distorts the electrode surface, and this affects both the electric and the thermal gradients in its immediate vicinity. In the present work, the distortion varied owing to movement of the wire within the hole while heating up, and through the assembly being dismantled between test runs; furthermore, the edges of the hole were affected by flashovers and heat.

(3.1) Hot Spot in a Uniform Field

The electric field was nominally uniform in Broadbent and Wood's experiments[3] at gap spacings of 2–6 cm (the spacing being smaller than the sphere radius). Their results, which are given for individual gap spacings but without indication of the scatter, have been translated into p.f.v. values, and lie between the curves marked (*b*) in Fig. 2. The results of several test runs

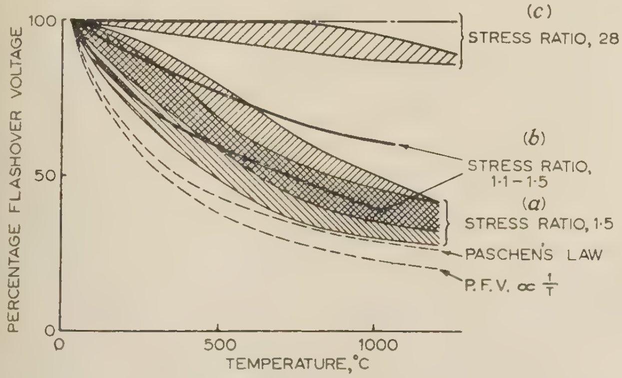


Fig. 2.—Relations between percentage flashover voltage and temperature.

(*a*) 0·5 cm gap between 2·5 cm sphere and earthed plate, with hot spot in plate.
\\\\\\ Sphere positive.
////// Sphere negative.

(*b*) Limits of area covered by curves for 2–6 cm gaps between 15 cm spheres, with hot spot in earthed sphere. Both polarities. [From Broadbent and Wood.[3] The stress ratio has been calculated on the assumption of field symmetry in the gap.]

(*c*) 8 cm gap between 2·5 cm sphere and earthed plate, with hot spot in plate.
——— Sphere positive (negligible scatter).
/////// Sphere negative.

The curve marked 'Paschen's law' is an estimate from that law, for a 0·5 cm gap, uniformly heated.

taken at a spacing of 0·5 cm in the present investigation are shown at (*a*) in Fig. 2, and will be seen to be in broad agreement with the earlier work, in that hot spots result in a very considerable lowering of flashover voltage in nearly uniform fields.

P.F.V. values were higher on negative than on positive polarity for the 0·5 cm gap, and a test run (with a 20 cm sphere and a 1 000° C hot spot in the plate) showed that this polarity effect was reversed at a gap spacing of approximately 2 cm, positive p.f.v. values being higher at bigger gap spacings. In Broadbent and Wood's work, positive values were also higher than negative values, by an amount which varied with the gap spacing; the data were consistent with a reversal of the polarity effect occurring just outside the range of spacings used (i.e. just under 2 cm). The same polarity effect has been recorded by Sletten and Lewis[6] for Trigatron gaps, the reversal having occurred at about 1·8 cm. This provides further support for the view that the operation of Trigatron gaps depends largely on the formation of a hot spot by the trigger discharge.

Fig. 2 includes a curve, estimated from Paschen's law, of the p.f.v. values obtained when a 0·5 cm uniform-field gap is heated throughout (as in Section 2). Similar curves, for larger gap spacings, would lie between the 0·5 cm curve and that obtained from p.f.v.'s proportional to $1/T$. It will be seen that, despite the large voltage lowering caused by hot spots, their effect is smaller than that due to heating the whole gap, and a little consideration will show that this must necessarily be so. A hot spot rarefies the air in its immediate vicinity, and thus reduces the electric stress required for ionization by collision. This stress cannot be less, and is in fact likely to be greater, than that required for ionization if the whole gap is heated to the hot-spot temperature; it is well known that the electric stress required for ionization is increased if ionization can occur along a short distance only (e.g. corona inception for thin conductors).[5] Furthermore, at atmospheric pressure there is no significant difference between the voltages required for ionization and for flashover, if the whole gap is heated. If there is only a hot spot, however, the ionization which occurs in its immediate vicinity is effective only in distorting the field in the remainder of the gap, and a higher voltage may well be required for flashover. Thus a hot spot can lower the flashover voltage to a value approaching, but not smaller than, that obtained by heating the whole gap.

(3.2) Hot Spot in Region of Minimum Stress

As the field departs from uniformity, the effect of the hot spot decreases. This is illustrated by Fig. 3, which shows that the

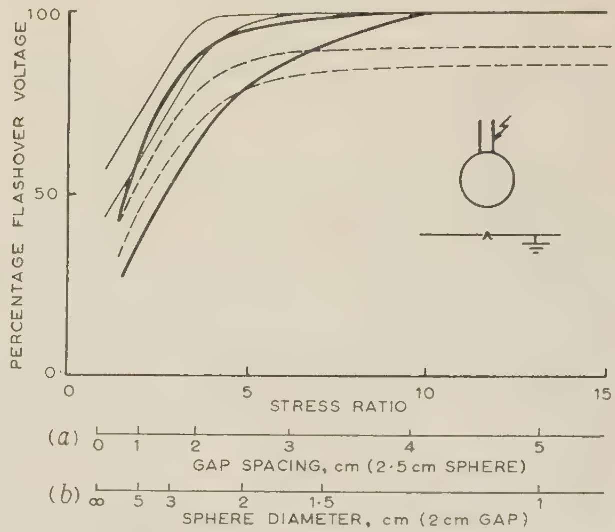


Fig. 3.—Relations between percentage flashover voltage and stress ratio, with a hot spot in the plate.

The curves are envelopes of the areas covered by the scatter of results.
▬▬ 2·5 cm sphere. 1 200° C hot spot. Positive voltage. The stress ratio was altered by means of the gap spacing, as shown by scale (*a*).
— — — As above, except negative voltage.
——— 2 cm gap. 1 000° C hot spot. Positive voltage. The stress ratio was altered by means of the sphere diameter, as shown by scale (*b*).

p.f.v. increases with increase in the stress ratio. The relation between these two quantities can be explained by means of a simplified analysis for which it is assumed, in the first place, that there is no significant difference between the voltages required

for ionization (in any part of the gap) and flashover, and that field distortion due to the hot-spot construction is negligible. The validity of Paschen's law, which has been demonstrated in Section 2, is taken to indicate that thermionic emission can be ignored.

In the absence of the hot spot, the electric strength is uniform throughout the gap, at a value E_c, so that flashover will be initiated in the region of maximum stress, i.e. near the sphere. The flashover voltage is given by

$$V_c = (\text{Mean stress}) \times (\text{Gap spacing})$$

and at flashover the maximum stress in the gap is equal to E_c, so that E_c/(Maximum stress) = 1, and therefore

$$V_c = \frac{E_c}{(\text{Maximum stress})} \times (\text{Mean stress}) \times (\text{Gap spacing})$$

If now a hot spot is introduced at the plate, it reduces the electric strength there to E_h, without affecting it near the sphere. Provided that the stress ratio is less than E_c/E_h, flashover is then initiated from the plate; consequently, E_h/(Minimum stress) = 1 at flashover, and the flashover voltage is

$$V_h = \frac{E_h}{(\text{Minimum stress})} \times (\text{Mean stress}) \times (\text{Gap spacing})$$

Hence the p.f.v. is given by

$$\frac{V_h}{V_c} \times 100\% = \frac{E_h}{E_c} \times (\text{Stress ratio}) \times 100\%.$$

Taking the electric strength of air to vary inversely with the absolute temperature (see Section 2),

$$\text{P.F.V.} = \frac{\text{Stress ratio}}{\text{Temperature ratio}} \times 100\%.$$

It is now possible to explain the data of Fig. 3, and positive voltages (full curves) will be considered first. The hot-spot temperature being fixed for a given curve, the temperature ratio is constant. Increasing the stress ratio therefore increases the p.f.v. until the latter reaches 100%; according to the above analysis, the stress ratio is equal to the temperature ratio at that point. Subsequent increase in the stress ratio has no further effect on the p.f.v. because flashover is now initiated near the sphere, so that the expression derived above ceases to apply. However, the stress ratios at which the hot spots cease to be effective have values of about 7 and 10, respectively (see Fig. 3), and to these there correspond temperature ratios of 4·3 and 5. The difference between corresponding ratios is due to the fact that the effective stress ratio is smaller than the values given in Fig. 3, because the hot-spot construction increases the minimum stress, while the maximum stress is decreased by corona. Nevertheless, the temperature ratio and the estimated stress ratio are of the same order, so that estimates as to whether a hot spot will affect a given electrode configuration can readily be obtained by comparing these two ratios; it can be seen from Fig. 3 that the lowering of flashover voltage due to the hot spot is less than 20% when the temperature and stress ratios are equal.

Pre-breakdown corona is much more intense on negative polarity, so that there is a greater reduction in the effective stress ratio. That is why the hot spot maintains a definite though small effect for negative voltages even at high stress ratios (see Fig. 3, dotted curves).

Flashover voltage is lower on positive than on negative polarity, so that it occurs on positive half-cycles of power frequency. Consequently, the relation between the p.f.v. and the stress ratio at power frequency is the same as for positive voltages; this conclusion was confirmed experimentally.

(3.3) Hot Spot in Region of Maximum Stress

Fig. 4 shows the results obtained with the hot spot in the sphere. Flashover is now initiated from the sphere under all

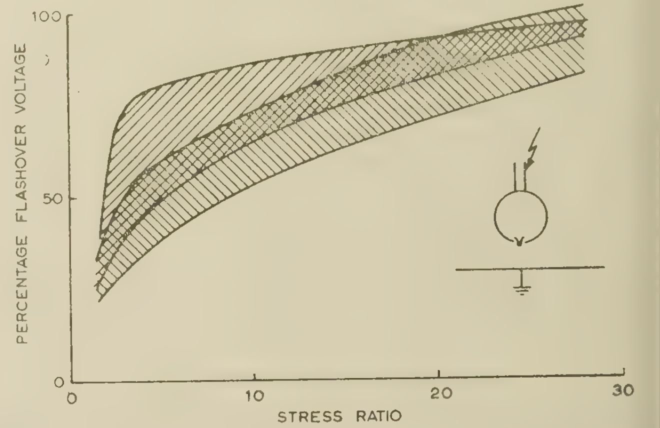


Fig. 4.—Relation between percentage flashover voltage and stress ratio, with a 1 200° C hot spot in a 2·5 cm sphere.

The stress ratio was varied by increasing the gap spacing from 0·5 to 8 cm.
\\\\\\ Positive voltage.
////// Negative voltage.

conditions, since the electric field is most intense there, and the electric strength is reduced by the hot spot. At low stress ratios, the field approaches uniformity as in Section 3.1 and the p.f.v. is low. At high stress ratios, there is considerable corona before breakdown; the hot spot lowers the corona inception voltage and increases the corona current, but does not otherwise affect the electric strength of air at the extremity of the corona region, where further ionization is required for breakdown. That is why the p.f.v. increases with increase in the stress ratio, as shown by Fig. 4; thus the p.f.v. exceeds about 40% when the stress and temperature ratios are equal (=5), and 80% when the stress ratio exceeds 28.

When the stress ratio was 10 or more, and the hot-spot temperature exceeded 700° C (other conditions being as for Fig. 4) a filamentary corona streamer developed from the sphere. Its length increased with voltage, and at a sufficiently high voltage it was continued by a diffuse glow up to the plate, so that a luminous glow spanned the gap, across which a high voltage was maintained. Increasing the voltage increased the mean value of the glow current, until transition to a spark occurred. The voltage at which this occurred was taken as the flashover value. Measurements taken at voltages just below flashover with a 1 000° C hot spot showed that the current consisted of pulses lasting for a fraction of a microsecond, and yielded values of the order of 10^{-1} amp for the pulse amplitude, 10^3 pulses/sec for the frequency, 10^{-8} coulombs for the charge carried by each pulse, and 10^{-5} amp for the mean discharge current.

An experiment was carried out at stress ratios of 1·5 and 28 with conditions as in Fig. 4 except that there were hot spots in both electrodes, at 1 000° C. The voltage lowering was substantially the same as that due to the more effective hot spot in the absence of the other one.

(4) CONCLUSIONS

Paschen's law has been confirmed for temperatures up to 1 100° C in air. Experiments in which the electric field and

temperature were substantially uniform throughout the test gap have yielded flashover voltages which are independent of electrode material and can be expressed in the form $V = Ax + B\sqrt{x}$, where x is proportional to the product of air density and gap spacing. Thus the same results are obtained at high temperatures as in experiments under atmospheric conditions and in which the voltage is varied principally by means of the gap spacing. To a first approximation, the formula can be written $V = Kx$, so that the electric strength of air becomes inversely proportional to the absolute temperature.

Hot spots have a pronounced effect in uniform fields: they reduce the flashover voltage to a value which may approach but cannot be smaller than that obtained by heating the whole gap to the hot-spot temperature. This effect decreases as the field departs from uniformity; in the most divergent field used in this work, the ratio of maximum to minimum stress in the gap was 28, and the percentage flashover voltage exceeded 80% for a 1 200° C hot spot on either electrode.

An approximate relation has been derived between the percentage flashover voltage, and the ratios of temperatures and stresses in a sphere-plate gap with a hot spot on the plate. This relation was confirmed by experiments which showed that when the stress ratio exceeded a value of the order of the temperature ratio, the hot spot ceased to affect flashover at power frequency, and also with direct current provided that the sphere was positive.

(5) ACKNOWLEDGMENTS

Acknowledgments are due to the Directors of A. Reyrolle and Co., Ltd., for permission to publish the paper; to Mr. H. Leyburn and Mr. A. F. B. Young for their interest in this work; and to Mr. S. Quogan and Mr. C. W. Powell for their able assistance.

(6) BIBLIOGRAPHY

(1) Bowker, H. C.: 'Variation of Spark Potential with Temperature in Gases', *Proceedings of the Physical Society*, 1930, **43**, p. 96.

(2) Frank, S.: 'Anfangsspannung und Gasdichte bei vershiedenen Elektrodenformen', *Archiv für Elektrotechnik*, 1929, **21**, p. 318.

(3) Broadbent, T. E., and Wood, J. K.: 'A Thermally Triggered Spark Gap', *British Journal of Applied Physics*, 1955, **6**, p. 368.

(4) Bruce, F. M.: 'Calibration of Uniform-Field Spark-Gaps for High-Voltage Measurements at Power Frequencies', *Journal I.E.E.*, 1947, **94**, Part II, p. 138.

(5) Peek, F. W.: 'Dielectric Phenomena in High Voltage Engineering' (McGraw-Hill Book Co., 1929).

(6) Sletten, A. M., and Lewis, T. J.: 'Characteristics of the Trigatron Spark Gap', *Proceedings I.E.E.*, Monograph No. 193 M, August, 1956 (**104** C, p. 54).

621.398 : 621.311.1

The Institution of Electrical Engineers
Paper No. 2626 S
May 1958
©

STANDARDIZATION OF CONTROL FACILITIES FOR THE BRITISH GRID: COMMUNICATIONS, INDICATIONS AND TELEMETERING

By P. F. GUNNING.

(*The paper was first received* 7*th October*, 1957, *and in revised form* 18*th February*, 1958. *It was published in May*, 1958, *and was read before the* Supply Section 28*th May*, 1958.)

SUMMARY

During 1932–57, different telephone, general indicating, and telemetering systems were used to control the British Grid. These systems served their purpose, but improvisations had to be made from time to time to cater for expansion of the Grid. Since 1938, the Grid has been operated as one interconnected system; it is now of 22 000 MW capacity and the rate of expansion shows no sign of diminishing. A readily extensible and standard system became necessary, and in 1949 the then British Electricity Authority embarked on a programme to re-equip about 300 stations, 8 Grid Control Centres and the National Control Centre with a 'standardized system' which provided many new features that operating experience had proved to be necessary.

The standardized system was developed by certain telephone manufacturers in consultation with the Authority. A full description of the facilities it provides is given in the paper. Reasons are also given why with few exceptions rented Post Office circuits are used for the control networks. A brief description is included of control facilities afforded by switchgear-reclosing equipment provided at unattended stations controlled by the standardized system.

The principal design features of the system are described in the companion paper.[7]

(1) INTRODUCTION

The British Grid became operational in 1932 and the country was served by the Central Electricity Board. For administration purposes the country, with the exception of the part of Scotland now operated by the North of Scotland Hydro-Electric Board, was divided into seven Districts (Fig. 1). Each District was a control area with a combined Grid Control Centre (G.C.C.) and District Headquarters situated near the principal load centre of the area (London, Bristol, Birmingham, Manchester, Leeds, Newcastle and Glasgow). These control areas remain substantially the same to-day (Fig. 2), except that in 1950 the South East Control Area became the 'Thames North' and 'Thames South' Control Areas served by the London control centre, and with the recent commissioning of the associated 275 kV system the Westmorland and Cumberland regions are controlled from Newcastle. The control areas were operated as separate Grid systems until 1938, since when they have been operated as one country-wide interconnected system, then 6 500 MW and now 22 000 MW, with the G.C.C.'s (except Glasgow since the creation of the South of Scotland Electricity Board in 1955) under the direction of a National Control Centre in London.

The G.C.C.'s, generating stations and transmission stations were equipped on a control-area basis from 5 different systems of general indicating, telephone and telemetering equipment.

These systems[1,2] used rented Post Office lines from the stations in the control area to a central trunk exchange and thence in a common cable to the G.C.C. in the suburbs. A simple emergency control centre was provided in the city near the trunk exchange against failure of the common cable.

Signals were automatically transmitted from the stations to

Fig. 1.—Grid control areas 1932 (C.E.B.).

indicate the condition of Grid circuit-breakers and the ta[p] positions of the on-load tap-changing Grid transformers. Com[-]munication with the G.C.C. and District Headquarters wa[s] provided from special telephones in the Grid stations and in th[e] control rooms of the associated power stations, which at tha[t] time were owned by power companies and local authorities. Also provided in the power station control rooms were instruc[-]tion indicators which responded to any of 7 instructions trans[-]mitted by the G.C.C. control engineers.

Torsion-balance continuous telemetering was provided in th[e] Birmingham control area; in the other areas the telemeterin[g] systems were of the 'on request' variety. The telemeters indi[-]

Mr. Gunning is with the Central Electricity Generating Board.

cated the active and reactive power transfers through the Grid transformers and on the inter-area Grid feeders; transmitters hand-set by the power station operators indicated total power generation. 'On request' telemetering of inter-area transfers was soon displaced by continuous telemetering systems (variable-frequency and phototelemeter in 1935 and impulse count in 1936).

The first Grid feeder-flow diagram became operational in 1937 at the National Control Centre in London for the display on a national scale of the power transfers between the different control areas. The first extensible system diagram using the mosaic principle was provided in 1936. Instruments indicating rate of change of system frequency were introduced in 1947.

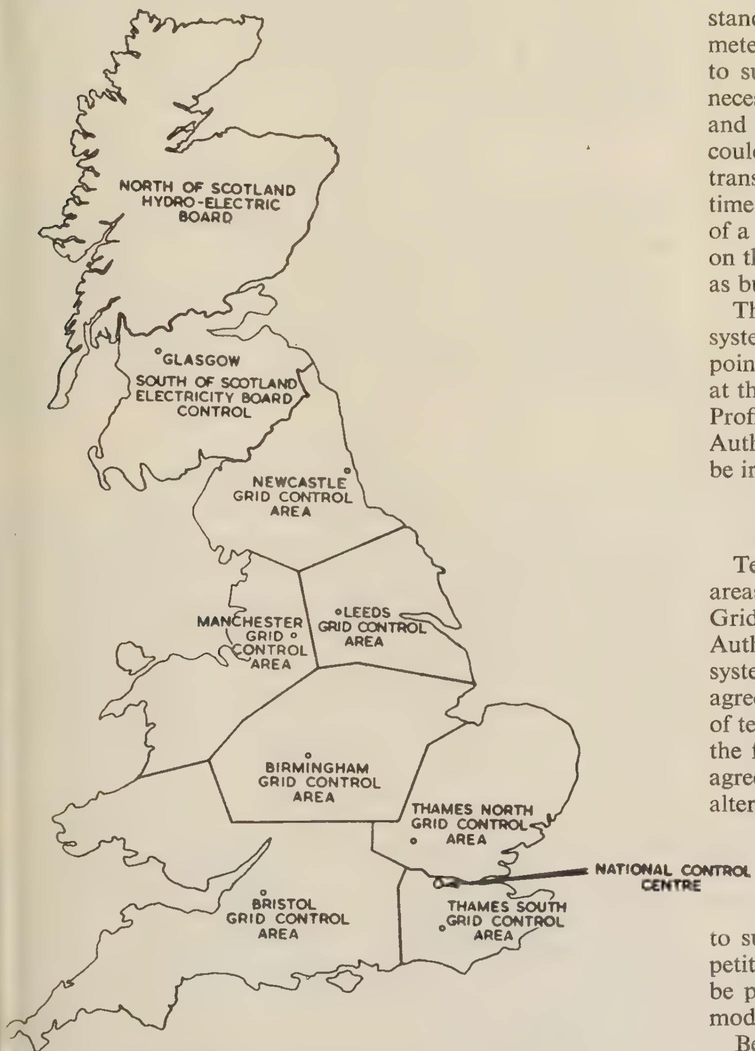


Fig. 2.—Grid control areas 1958 (C.E.G.B., S.S.E.B. and H.E.B.).

With the expansion of the Grid, particularly during the war, individual installations had to be modified from time to time, and the cost and engineering effort expended emphasized the need for a readily extensible and standard system for general indications, telephones and telemetering.[4]

In 1948 the electricity supply industry was nationalized and the C.E.B. Districts were replaced by 14 Generating Divisions, but the 7 Grid control areas remained unchanged. For administration purposes the change in ownership made it necessary to provide communication facilities between the generating stations and the new Divisional Headquarters. The 7 C.E.B. District Offices with Grid control networks became Divisional Headquarters, but temporary communication arrangements with their stations had to be provided either direct or via the G.C.C.'s in the neighbouring Divisions for the Divisional Headquarters in Cardiff, Liverpool, Edinburgh, Nottingham, Portsmouth and outer London.

(2) THE STANDARDIZED SYSTEM

(2.1) General

The British Electricity Authority decided in 1949 to re-equip the Grid control networks, then more than 15 years old, with a standard system of general indicating, telephone and telemetering equipment which could be extended from time to time to suit changing conditions. This large-scale programme was necessary because (*a*) the cost and engineering effort to modernize and extend the existing installations throughout the country could not be justified, and (*b*) a large number of generating and transmission stations were to be built to make good the wartime standstill and it was necessary to meet the requirements of a country-wide 275 kV Grid system (soon to be superimposed on the 132 kV Grid) and of many small Grid stations to be built as bulk supply points for the new Electricity Boards.

The Authority authorized the installation of a standardized system in all generating and Grid stations and some supply points to the Electricity Boards, and because of the congestion at the existing G.C.C.'s decided to build new and larger centres. Profiting from experience of Grid control in war time the Authority located the new centres in districts where they would be independent of central trunk exchanges.

(2.2) The Telecommunications Technical Committee

Telephone manufacturers who had equipped the Grid control areas at the outset* and were experienced in the development of Grid control equipment were invited to co-operate with the Authority in the design and production of a 'standardized system', as it came to be called. This approach resulted in an agreement which (*a*) permitted the free interchange and use of technical information between the manufacturers, (*b*) ensured the further development of the system for the duration of the agreement and (*c*) safeguarded the system against arbitrary alterations.

The Authority and the telephone manufacturers concerned set up a Telecommunications Technical Committee (T.T.C.) to be responsible for the design of the standardized system, for the development of the system to suit changing requirements and to keep in step with competitive developments. The Authority specified the facilities to be provided by the system, and from time to time these were modified to suit changing power system requirements.

Because of the large development programme and to eliminate duplication of effort, the design of the standardized system was shared by the manufacturers on the basis of

(*a*) Communications and G.C.C. apparatus.
(*b*) Line signalling and transmission, general indications and outstation apparatus, and
(*c*) Telemetering, miscellaneous instrumentation and power supplies.

It became evident in view of the complex variety of stations and network conditions, that the standardized system could not be a precise installation with universal application, but would instead be the rigid standardization of many different items of equipment which would be installed in different combinations to suit the requirements of different stations. As each item

* Automatic Telephone and Electric Co. Ltd., General Electric Company Ltd. and Standard Telephones and Cables Ltd.

of equipment was agreed its subsequent development under T.T.C. supervision became the responsibility of the manufacturer concerned. When sufficient items had been codified and the planning parameters of the new system determined, the Authority was able to plan the individual Grid control networks and to issue the various contract specifications. On the planning parameters depended the ultimate success of the standardized system in being able to meet any station or network problem in the country.

(2.3) The Standardized System

The standardized system was designed to use ordinary-grade Post Office lines with

(*a*) Earth-return phantom d.c. signals for the infrequent traffic of general indications, visual instructions and telephone calls. On lines where d.c. signalling could not be used, 300 c/s was used instead with 400 c/s high-pass speech filters;
(*b*) Above-speech v.f. signalling for high-density telemetering traffic using time-division multiplex 50-baud transmission for 10 continuous readings on a single 120 c/s bandwidth channel.[5]

The principal design features of the standardized system are covered by the companion paper.[7]

In the interests of general economy of line plant and security

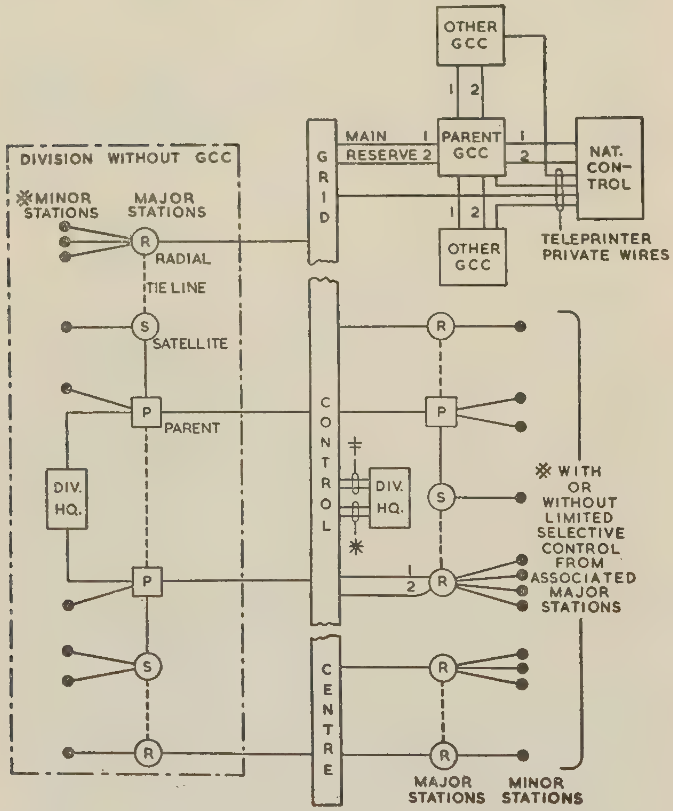


Fig. 3.—Typical communication network for a Grid control area.

Transmission loss (including G.C.C. and station equipment) not to exceed 20 dB between G.C.C. and major stations, or 25 dB to major stations over tie lines or to minor stations over direct routes.
ǂ Low-loss junctions for automatic communication with stations in Division.
∗ Inter-P.A.X. junctions.

of communications, and of the provision of facilities for administration traffic it was decided (see Fig. 3):

(*a*) To adopt group working for the more distant stations with a limit of four stations in a group, three being direct satellites on the parent station, which would have a line to the G.C.C.
(*b*) To cater for inter-station communication within a group, but to arrange for such communication to be overridden by calls to and from the G.C.C. and to allow the internal telephone systems in power stations to use the network to communicate with the G.C.C., the Divisional Headquarters and other stations.
(*c*) To reinforce communication with major stations using tie lines between stations each served by separate line to the G.C.C.
(*d*) To arrange, in Divisions with G.C.C.'s, for the telephones at the Divisional Headquarters to have automatic use of the G.C.C. equipment for communication with stations in the Division, and, in Divisions without G.C.C.'s, for the telephones at the Divisional Headquarters to have local access to the control network in the Division for communications with the local stations.
(*e*) To develop a cheaper system for small (minor) stations as an extension on nearby major stations. There was a steadily increasing number of small Grid stations erected to give bulk supplies to the new Electricity Boards, and it was wasteful of rented lines and equipment to provide major station equipment at stations which required only a telephone and a few general indications and perhaps a telemeter or message instructor.
(*f*) To make it possible for control staffs at major stations to control the associated minor stations, since it would have been grossly uneconomic to employ local attendants or provide pilot cables and comprehensive supervisory control equipment.

(2.4) The Associated Equipment Programme

Because of the large programme confronting the manufacturers, the Divisions undertook responsibility for the provision of the associated equipment specified by the T.T.C. This included the installation and setting to work at outstations of telemeter initiating devices, overload relays, telephones, instruments and instructors on power station control desks, batteries and distribution boards, chargers and power supplies, cabling and connections to power station P.A.X.'s and Grid switchgear.

(3) CHANNELS OF COMMUNICATION

(3.1) Lines Rented from the Post Office

The Authority (now the Central Electricity Generating Board) generally employs lines rented from the Post Office for the Grid control networks because with the complex power-system configurations and the large numbers of stations in the control areas there is no practical alternative.

From their very nature, rented telephone lines cannot be as reliable or as free from accidental interference as pilot cables but their use for Grid control purposes during the last 25 years has been very satisfactory and has demonstrated the following advantages:

(*a*) Without loss of investment unwanted lines can be surrendere and new lines rented to suit network development.
(*b*) Throughout the Generating Board's territory, reliable lines if necessary with zero loss, can be made available by the Post Offic over any distance and often at short notice.
(*c*) Over the average distances involved, rented lines usuall permit the use of simple d.c. signalling equipment and are con siderably cheaper than pilot cables or power-line carrier systems.
(*d*) Unlike carrier or radio installations, rented lines ar unaffected by the frequent diversion or teeing of Grid lines to su system development.
(*e*) Being mostly underground, rented lines are immune fror disturbances due to power interference, or atmospheric condition (including weather), nor do they require optical propagation path or expensive supplies.
(*f*) Apart from circuit testing and fault reporting by th Generating Board, lines are maintained by the Post Office, who giv priority treatment to faults on the Board's circuits and on occasio are able to make a replacement available during a repair outage.
(*g*) Reserve lines over alternative routes or cables can be mac available with dual-entry cables into important stations.
(*h*) G.C.C.'s do not need to be sited adjacent to power installation

Lines for Grid control purposes are rented at the norma provision tariff, but the rental is increased when low-loss (4-wir transmission has to be provided on a section normally serve by 2-wire transmission. Rentals are calculated on the distanc between stations, except for those lines which have to be special

routed for network reinforcement to avoid routes of normal provision, in which case the rental is based on route length. Where line plant is provided in excess of that required for normal expansion of public exchange requirements the Post Office may require the Board to pay for the work in the form of a rental over the first few years.

The Post Office can generally provide lines suitable for transmission up to 2400 c/s with the loss at this frequency not greater than 10 dB relative to that at 800 c/s. Such lines are suitable for the simultaneous transmission of speech, telemetering and general indications. Very often rented lines are suitable for 3000 c/s transmission, but apart from a few stations where more than 20 telemeters are required, advantage is not taken of this because the standardized system has been designed for lines of average performance. Mismatching transformers to flatten frequency-response are provided at the ends of long unloaded renter's-end cable, which would otherwise degrade the performance of 4-wire lines.

(3.2) Underground Pilot Cables

Because of their greater reliability, underground pilot cables are preferred to rented lines for Grid control purposes, but are only provided when the otherwise prohibitive installation cost can be justified for such other services as feeder protection or supervisory control or can be considerably reduced by making use of power-cable laying operations. Because of the high cost of pilot cable installation the Authority was generally obliged to use rented lines for pilot-wire systems of feeder protection.

(3.3) Aerial Pilot Cables

Except for a short experimental section of earth conductor with embedded pilots, there are no aerial pilot cables on the Grid transmission towers in Great Britain. Catenary-supported cable and self-supporting cable cannot be erected on existing transmission towers without a reduction in the factor of safety of about 10%. With aerial pilot cables, joints cannot be made in mid-span. The possible effects of falling conductors or low-flying aeroplanes have to be accepted; and it is necessary to isolate the terminal equipment against dangerous voltages appearing during system disturbances.

(3.4) Power-Line Carrier Systems

Power-line carrier communication and signalling is economic over long distances and is the only means generally available in undeveloped or mountainous territory. In Great Britain the widespread use of power-line carrier systems for Grid control purposes would be expensive, since the majority of Grid lines are short, or soon become so with system development. The use of power-line carrier systems could probably be justified in a few favourable instances if the main cost could be borne by system protection and if there was some guarantee that the Grid system in the neighbourhood would remain substantially unaltered for the foreseeable future. Despite the undoubted reliability of power-line carrier systems, as evidenced by their widespread use abroad, basic technical disadvantages would have to be accepted, such as:

(*a*) Increase in signal attenuation during icing conditions, which can be very serious on long lines at the higher carrier frequencies.

(*b*) Loss of service during power line maintenance.

(*c*) Inability to use the same carrier frequency on lines inductively coupled by the power network. In a complex and expanding Grid system this can be a planning restriction having regard to the limited frequency spectrum available for reliable carrier transmission.

(3.5) Radio

Fixed-to-mobile v.h.f. transmission has proved to be most useful for transmission construction and maintenance, but only under exceptional circumstances, when reliable line transmission cannot be made available, will the Post Office permit the use of fixed-to-fixed radio transmission. It would be of great assistance if major stations affected by failure of normal communications, as for example during the East Coast floods of 1953, could communicate by radio with other stations where messages to and from the G.C.C. could be repeated. Depending upon the band in use, frequency- or space-diversity reception or both may be necessary to combat fading should the transmission path be long and over water, but these conditions are only likely to arise in association with submarine power projects.

(4) COMMUNICATION NETWORKS FOR GRID CONTROL AREAS

In the network planning of the standardized system the outstations in a Grid control area are defined as either major stations or minor stations (Fig. 3). A major station is usually a generating station with or without a Grid station, or a large attended Grid station not associated with a generating station. Only major stations can send signals to, or receive signals from, a G.C.C. A major station usually has a direct line to the G.C.C., in which case it is termed a radial station, and has also a direct line to each minor station associated with it, usually not more than three or four. A minor station is usually a small Grid switching and transforming station or a bulk supply point to an Area Board. A minor station can only send signals to, or receive signals from, a major station.

To economize in rented circuits the more distant major stations can be connected in groups usually of 2, but up to a maximum of 4 stations. A group is served by a common line from the G.C.C. to the nearest or most important station in the group, and from this parent station (as it is called) by separate lines to each of the other stations in the group, which are known as satellite stations.

For their mutual reinforcement, pairs of major stations served by separate lines to the G.C.C. are interconnected by tie lines. These lines provide an alternative although indirect means of communication between the G.C.C. and the major stations, together with their minor stations. The more important radial stations may be provided with second lines to the G.C.C., switched to take over service on instruction from the G.C.C. over the reserve line should the normal line fail. In normal use, reserve lines operate as inter-P.A.X. tie lines between the G.C.C. and the stations. Tie lines and reserve lines are routed by the Post Office to avoid cables containing Grid control lines.

Groups of stations in a Division without a G.C.C. are usually connected by local lines to the telephone board at the Divisional Headquarters, where the operator extends calls between the stations and the Divisional Headquarters P.A.X. telephones. This arrangement confines the administration traffic within the Division and increases the usefulness of tie lines, parent-satellite lines and major-minor lines which group the stations for Grid control purposes. Grid control traffic takes priority over inter-station and Divisional traffic.

In Divisions with a G.C.C., inter-P.A.X. tie lines are provided between the Divisional Headquarters and the G.C.C. Low-loss 4-wire junctions are also provided so that the Divisional Headquarters P.A.X. telephones can dial into the standardized system at the G.C.C. to initiate calls to any outstation control telephone or to any power station telephone operator in the Division. Calls to the Divisional Headquarters from the outstations are received at the G.C.C. and relayed over these junctions to a cordless telephone board at the Divisional Headquarters, where the telephone operator extends the calls into the local P.A.X. This Divisional traffic does not require the services of the telephone operator at the G.C.C., and although it makes use of the

control apparatus and the Grid control network, it does so on a non-priority basis so as not to inconvenience Grid control traffic.

The existing radial network based on London from National Control to each of the G.C.C.'s is to be replaced by a network which will provide communication facilities between neighbouring G.C.C.'s and, if necessary, will probably cater for standby National Control Centres as required. The new network (Fig. 4)

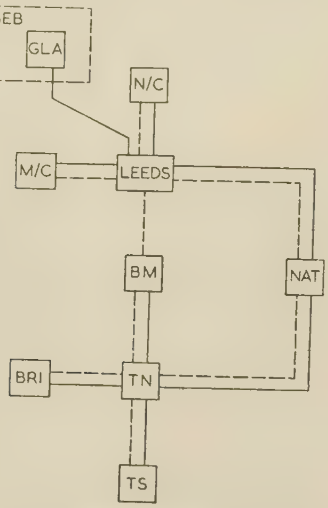


Fig. 4.—National control network.

will primarily cater for the full-scale transmission of general indications, telephony and telemetering to a new National Control Centre in London from the various G.C.C.'s, and will provide communication and standby telemetering facilities between the South of Scotland Electricity Board's G.C.C. at Glasgow and National Control. As far as traffic limitations permit, the separate Divisions and the Generating Board's Headquarters in London will be able to communicate with each other on the new network.

The Post Office private-wire teleprinter network from National Control to each G.C.C., which has been in service for over 20 years, will be retained to reinforce the new network.

(5) STANDARD FACILITIES IN GRID CONTROL CENTRES

(5.1) General

In the following description of the facilities provided by the standardized system it should be understood that the new National Control Centre is not yet in commission.

In each of the new Grid control rooms there is

(*a*) A mosaic switching diagram.
(*b*) A feeder flow diagram.
(*c*) A miscellaneous instrument and recorder suite.
(*d*) A switching desk, or desks.
(*e*) A loading desk.
(*f*) A clerk's desk.

In each Grid control area the system operation engineer specified the layout and appearance of the control desks, dia-

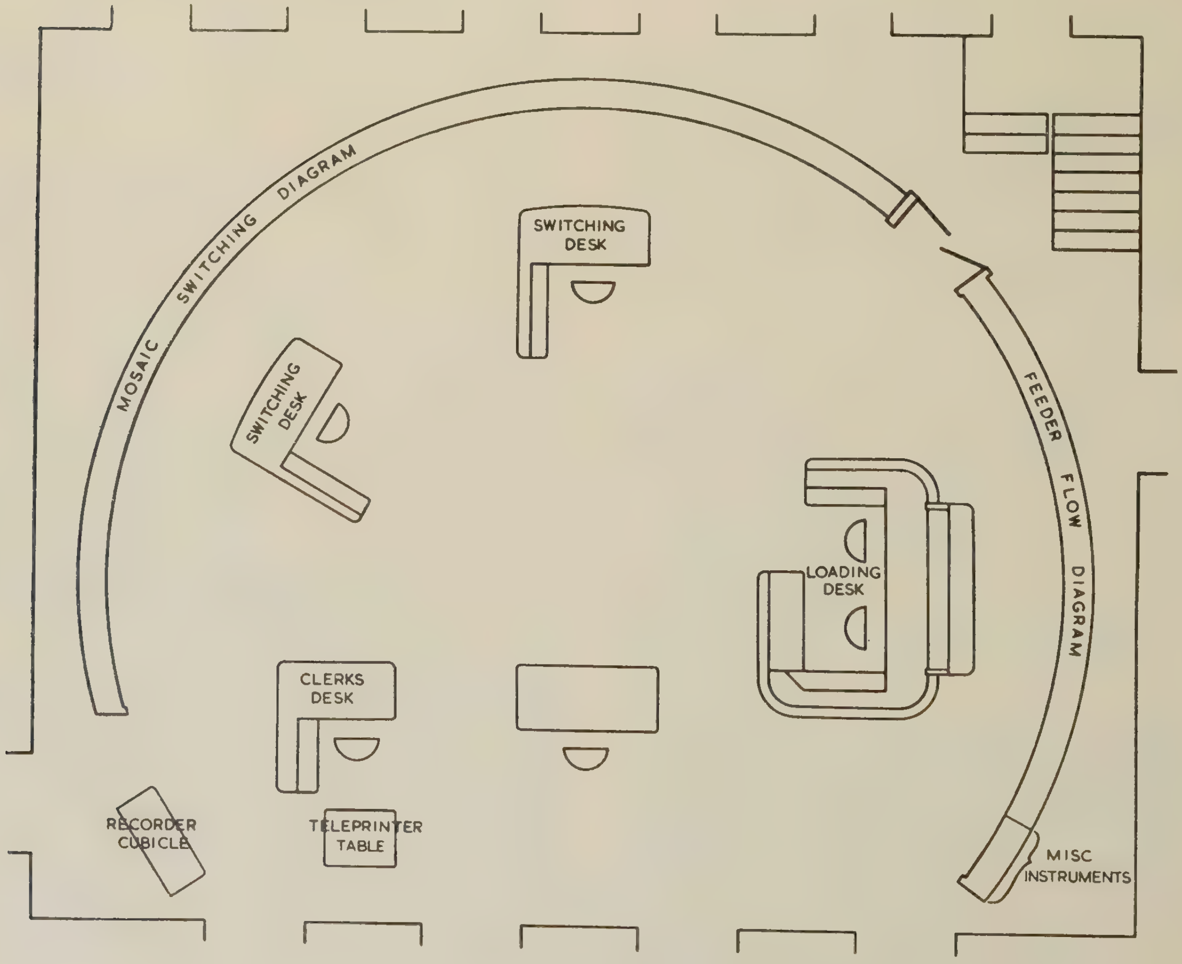


Fig. 5.—Plan of Thames North control room.

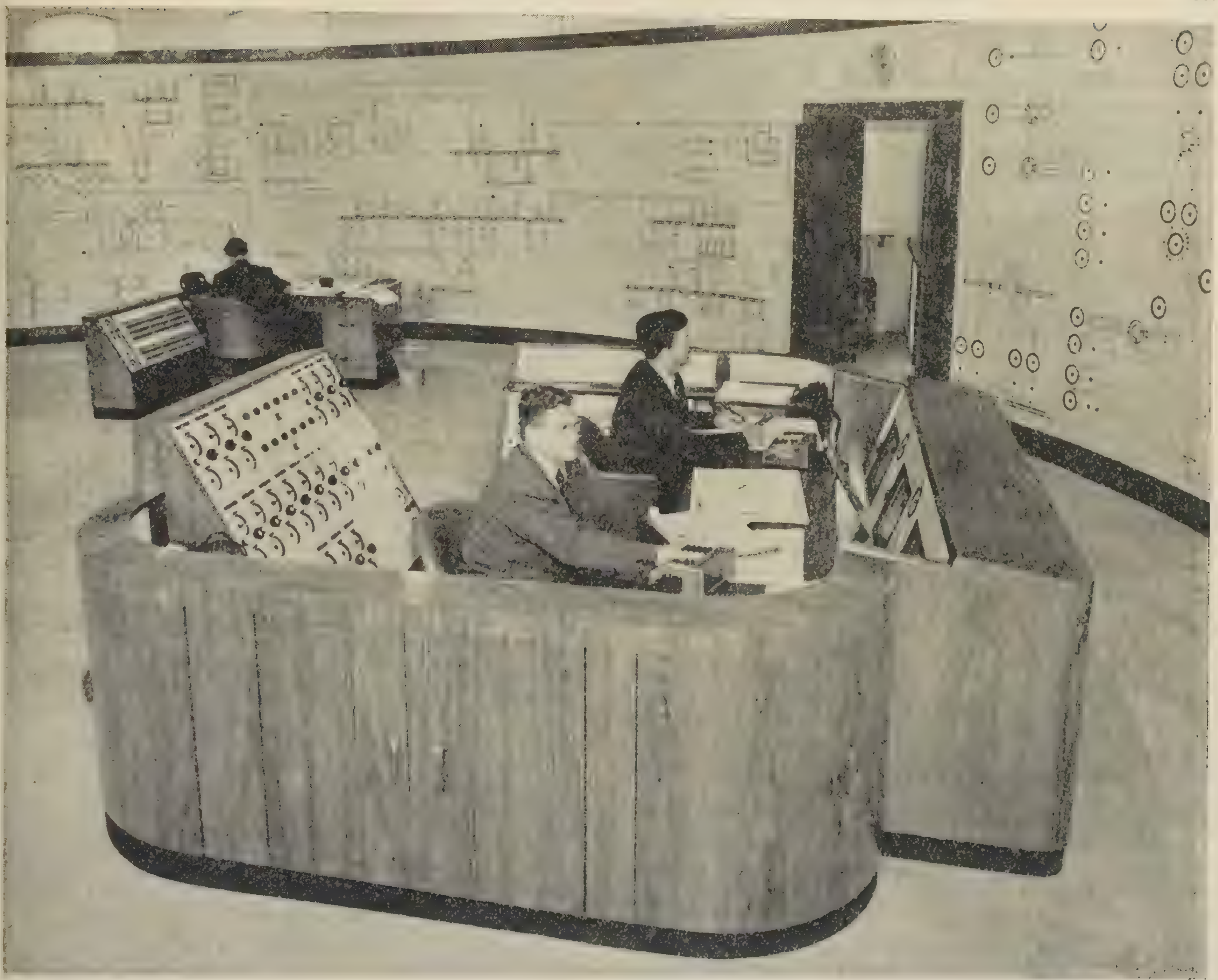


Fig. 6.—Loading desk.

grams and general furniture in the G.C.C. control room. This resulted in a variety of control-room arrangements, and the refreshing departure from uniformity did not in any way affect the standardized system. As an example, a plan of the Thames North control room is shown in Fig. 5, and a view of the loading desk in Fig. 6.

(5.2) Mosaic Switching Diagram

Similar to those introduced in the late 1930's for service in the London, Manchester, Bristol and Glasgow Grid control centres, mosaic diagrams display in detail in schematic form the Grid system and generating stations of the control area. A mosaic diagram comprises many thousands of 1 in plastic squares of a pastel shade; most are blank but some are engraved to portray circuit-breakers, isolators, earthing switches, generators, transformers, reactors and sections of line or busbar, and coloured to represent the appropriate system voltage. By replacing blanks with symbols it is a simple operation to keep the diagram in step with system development. The circuit-breaker symbol is a manually operated semaphore with a lamp which flashes when the semaphore is 'in discrepancy' with the position-indicating signal, which is automatically sent from the outstation whenever the particular circuit-breaker opens or closes. The switching engineer extinguishes the flashing light by correcting the semaphore. For a typical control area comprising 20 generating stations and 30 Grid transmission stations, the average 1 in-mosaic switching diagram is about 50 ft long by 9 ft high with 1 500 semaphores for circuit-breakers, isolators and earthing switches. Usually about 500 automatic indications are provided. These are for

(*a*) Circuit-breakers for 275 and 132 kV and the lower-voltage side of the Grid transformers.

(*b*) The automatic isolators associated with fault throwers.

If a bench diagram is preferred to a wall diagram, the mosaic squares are $\frac{1}{2}$ in with the discrepancy lamps mounted in squares adjacent to the circuit-breaker symbols.

A 2-tone chime alarm operates on the incidence of any change of circuit-breaker position, and can be repeated at regular intervals of 10 or 30 sec, as required, until the semaphore is corrected by the switching engineer. Meanwhile the station name on the diagram is illuminated, and a large annunciation 'circuit-breaker' is displayed centrally in the control room. Should the auxiliary contacts of a circuit-breaker be faulty, the corresponding semaphore will light steadily and there is no flash or alarm with the semaphore in either the 'closed' or the 'open' position. At any time, and particularly after equipment

outage for maintenance, the switching engineers can operate check keys on their desks to bring back automatic signals from any outstation to check the semaphores. A convenient lamp test is provided by which the semaphore lamps light during the checking cycle until their positions have been automatically confirmed, at which time they go out if the semaphores are in the correct position, and if not they flash until corrected by the switching engineer.

(5.3) Feeder-Flow Diagram

An animated feeder-flow diagram was first used at National Control in 1937. The usual flow diagram is a straight-line schematic on a pastel background showing the area transmission system with the lines coloured to represent the appropriate system voltages. At each station on the diagram, represented by small circles or rectangles, each line has a green 'line-end-open' lamp which lights automatically whenever the corresponding Grid line is open-circuited by the station switchgear. Telemeters positioned in the mimic power lines indicate the magnitude and direction of active and reactive power flow in the various 275 kV power lines and transformers and in the majority of the 132 kV lines. The telemeters have 270° movements with centre-zero scales and the pointers are deflected in the direction of flow. The scales are usually 600, 120 and 100 MW or 300, 60 and 50 MVAr respectively for 275 kV lines, 275 kV transformers and 132 kV lines. Each telemeter has a lamp to warn the loading engineer when it is out of service. A typical feeder-flow diagram has about 100 telemeters and is 25 ft long by 9 ft high, constructed of 6 in plastic or 20 in steel square tiles. With 6 in tiles the diagram can be readily changed, but with 20 in steel panels greater flexibility in the positioning of the telemeters is possible, leading to clearer presentation of a congested flow diagram; also magnetic symbols can be used to depict station busbar arrangements or transmission limitations.

Most mimic power lines on the diagram have a red lamp which flashes whenever the current in the corresponding Grid line exceeds a preset value between 80 and 160% of normal full load. The chime alarm operates and 'overload' is displayed on the central annunciator. The loading engineer is obliged to acknowledge the signal by operating a common 'accept' key. This stops any regeneration of the chime and extinguishes the annunciation display, and the flashing overload lamp changes to a steady glow which will not go out until the current in the particular Grid line falls below 90% of the preset value.

(5.4) Miscellaneous Instrument and Recorder Suite

The miscellaneous instrument and recorder suite, which is sometimes a continuation of the feeder-flow diagram, accommodates continuous-balance 10 in strip-chart MVAr indicator-recorders of area net transfer and area total generation. Small 3 in strip-chart recorders are provided for each 275 kV inter-area-feeder MW telemeter, and also for switching into regional system-frequency or system-voltage telemeters and for connecting into individual feeder-flow or station total-generation telemeters. In some of the G.C.C.'s a 3 in recorder is used to record the passage of lightning storms as detected by special radio equipment.[3]

Miscellaneous instruments accommodated on the suite include

(*a*) System-voltage and system-frequency telemeters from each region of the control area. The voltage scales are square-law with zero suppression, 100–160 kV and 200–320 kV for 132 and 275 kV sources respectively. The remote frequency telemeters are only intended for use under emergency 'system split' conditions and are scaled 45–52 c/s.

(*b*) Large circular-scale (28 in long) continuous-balance instruments which indicate system frequency (47–51 c/s correct to 0·01 c/s) total area generation and area net transfer. These instruments are standby to the 10 in indicator recorders on the loading desk.

(*c*) A cyclometer system-time-error indicator and synchronous clocks with centre-sweep seconds hands displaying system time and crystal-controlled time.

(5.5) Switching Desk

Facing the switching diagram is a control desk for each of the two switching engineers. In some G.C.C.'s these switching desks are combined to form one structure. Switching desks usually look bare because they are devoid of instruments other than Post Office and internal P.A.X. telephones, a telephone for the Grid control network and a 24-hour cyclometer logging clock. On a wing of the switching desk is a keyboard console on which the switching engineer can selectively call any control telephone in the area (see Section 6.1) and answer any kind of call from the network. For each major station there is a green calling lamp and a white busy lamp, and call keys as follows:

(*a*) One for each control telephone at the station.

(*b*) One for the telephone operator, should the outstation be a power station.

(*c*) One for calls via the major station to a neighbouring major station over a tie line mutually reinforcing the two stations.

(*d*) One for each associated minor-station control telephone.

Operation of any of the call keys associated with a major station will answer any kind of call from the station or its minor stations. Similar lamps and call keys are provided for calls to and from National Control.

The calling lamps flash for calls to the switching engineers and light steadily for calls to the loading engineers. The busy lamps flash for calls to the telephone operator in the G.C.C. office or at the associated Divisional Headquarters and become steady when the calls are answered by the operators concerned, remaining alight until the connections are released by the outstation callers. The control engineers can forcibly release any established connection and can call any control telephone at any station in the area, even though it may be in use or the hand-set has been left off the rest. Standard ringing and busy tones are observed throughout the telephone system.

To minimize distraction in the control room, calls from the network are signalled by a short buzz and 'telephone' is displayed on the central annunciator. The short buzz can be dispensed with altogether or can be regenerated every 10 or 30 sec until the call is answered.

The keyboard consoles have check keys for each major station to enable the control engineers after equipment outage to bring back signal trains from the various stations to confirm the circuit-breaker indications (see Section 5.2) and the directions of flow indicated by the telemeters on the feeder-flow diagram (Section 5.3). On one keyboard console there is a remote control panel for a 12 kW standby Diesel-driven alternator with a voltmeter indicating the Area Board mains supply to the G.C.C. The voltmeter has a segment of the scale coloured green to remind the control engineer of the voltage limits beyond which he must change over the control-centre apparatus to the standby alternator. The control panel has start, stop, on-load and off-load pushbuttons, and lamps to indicate 'Diesel running', 'on-load', oil-pressure failure, excess water-temperature and 'no-standby', and there is also an ammeter to indicate load on the alternator. During mains failure and until the Diesel is on load, lamps energized from the 50-volt battery light automatically in the control room to enable the control engineers to operate the Diesel control panel (similar facilities are provided in the apparatus room and Diesel house). A 'mains volts' alarm is displayed on the central annunciator during mains failure or low mains voltage. There is a similar control panel on the other switching desk for a 25 kW Diesel-driven alternator which

supplies the domestic needs of the establishment during mains failure and also serves as standby to the G.C.C. apparatus during overhaul of the 12 kW set. The domestic Diesel set is installed in the office block and is arranged for automatic starting and load change-over.

(5.6) Loading Desk

The loading desk in front of the feeder flow diagram usually has accommodation for two loading engineers. Each engineer has a logging clock, three telephones and a keyboard console similar to those used by the switching engineers, the only difference being that the calling lamps flash when calls are for the loading engineers and are steady for calls to the switching engineers. In the desk facing the loading engineers are 10 in indicator recorders for area net transfer, area total generation and system frequency. (Typical scales are respectively 1 000–0–1 000 MW import-export, 0–3 000 MW generation, and 48·5–50·5 c/s correct to $\pm 0{\cdot}005$ c/s.) Each of these recorders has a target pointer with an external knob for adjustment by the loading engineer. A potentiometer in the total-generation recorder automatically controls a telemetered transmission to National Control. The net-transfer indicator-recorder has as many supervisory lamps as there are inter-area feeder telemeters contributing to the net-transfer indication. These lamps light when the corresponding telemeter is out of service. Associated with the recorders are instruments indicating positive and negative rate of change of system frequency, scaled 0·2–0–0·2 c/s/min, and daylight intensity (as telemetered from the main industrial load centre of the control area), scaled 0–100 klx with 0–40 occupying 90% of the scale length. There is also a continuous indication of system frequency from an amplified system-frequency-modulated v.f. signal transmitted from a Grid station. At any time, the loading engineers can use the amplified signal instead of the local mains to energize the system-frequency instruments, a change which is automatically made in the event of mains failure.

There is a 4-digit cyclometer to indicate instructions from National Control of area generation, or area net transfer as the case may be, with a lamp which will flash on each alteration and light steadily when the answering button is operated to signal National Control that the instruction has been acknowledged. There is also a message instructor from National Control comprising sixteen combined buttons and lamps on which any of sixteen instructions, broadcast from National Control to any number of G.C.C.'s, are received and acknowledged. The loading engineer can at any time re-light the last instruction received.

From time to time, as the loading engineer alters his instructions to generating stations, he will be able to transmit his revised generating costs to the National Control engineers who then, if necessary, can revise their generation instructions to the other G.C.C.'s, using the 4-digit instructors. To display his costs at National Control the loading engineer adjusts two sets of decade switches, one for incremental and the other for decremental costs. Each set has switches for 100's and 10's of megawatts and for the cost of a unit expressed as a penny plus a decimal fraction to three places. After adjusting the megawatt and cost switches the loading engineer operates a button to send the revision to National Control, where it is to be displayed on cyclometer indicators and automatically tabulated on page-printing equipment, together with the identity of the G.C.C. concerned. The National Control engineer will be able to initiate signal trains from any G.C.C. to check the displayed costs. The page-printing equipment at National Control will also tabulate with time and identity of the G.C.C.'s concerned any generation, net transfer and 16-way message instructions transmitted from National Control.

On the loading desk is a 16-way message instructor on which the loading engineer can set up any of sixteen stereotyped instructions for broadcasting to any number of attended stations, and observe individual station acknowledgments. When the 'warning' instruction is sent it is displayed continuously at the outstation until the 'conditions now normal' instruction is received; meanwhile other instructions may be sent and acknowledged. On the loading desk, lamps indicate the stations where the warning instruction is being displayed.

On a console adjacent to or combined with the loading desk are the individual station-generation instructors and telemeters (megawatts 'sent out', megavars 'gross'). The instructor is a manually adjusted pointer superimposed on the megawatt telemeter scale and geared to a transmitter coding mechanism. To send a change-of-generation instruction to a station the loading engineer sets the pointer and operates the 'send' twist-button. Acknowledgment from the station is signalled by a lamp, and the loading engineer then resets the send button. A third pointer on the megawatt telemeter scale, which the loading engineer can set, serves to remind him of the maximum generation available at the particular time.

(5.7) Clerk's Desk, House P.A.X. and Telephone Operator's Boards

A desk is provided for the control engineers' clerk whose duties include operation of the National Control teleprinter. When the G.C.C. telephone operator is off duty the clerk, on a 3 + 9 Post Office board, deals with external calls, and on a private cordless board answers calls from the control network and extends them to G.C.C. telephones or other stations in the area by dialling into the house P.A.X. As a concession by the Post Office, facilities are provided so that in an emergency after office hours the clerk acting for the control engineers can, on one telephone extension of the 3 + 9 board, couple the telephone systems together to permit engineers at stations to talk to engineers at their homes.

Besides providing automatic intercommunication for the G.C.C. offices, control and apparatus rooms, the house P.A.X. enables the day staff to dial any control telephone or power station telephone operator in the control area or P.A.X. telephone at the local Divisional Headquarters. By means of the house P.A.X. the staffs at the different G.C.C.'s will be able to communicate with each other over the National Control network. The G.C.C. telephone operator has a Post Office board for the public system and a cordless board for receiving calls from stations, and can extend them to local telephones or telephones at outstations by dialling into the house P.A.X. The operator does not have to release these connections, the cordless board being cleared automatically by the outstation calling party.

(6) STANDARD FACILITIES AT OUTSTATIONS

(6.1) Control Telephones and Power Station P.A.X. Telephones

'Control' telephones, as they are termed, are provided at all outstations. They afford the following facilities:

(*a*) They can be called by the G.C.C. or the associated Divisional Headquarters even when engaged on calls to other telephones or left off the rest.

(*b*) They can call the G.C.C. loading and switching engineers or the G.C.C. and Divisional Headquarters telephone operators by dialling single digits to initiate selective calling trains. Should the line be engaged, the user, by dialling an additional digit, can exercise priority, but only to call the G.C.C. engineers. If the control engineer is already talking to the station the call will intrude into his conversation and he is made aware of the intrusion by

the calling signal, which he can clear by momentarily restoring his speaking key. Priority calls automatically disconnect conversations between non-operational parties, who receive busy tone until they restore their telephones.

(*c*) They can call the G.C.C. engineers or telephone operators (Divisional Headquarters or G.C.C.) via a neighbouring major station over a tie line.

(*d*) They have conference facilities such that when called they can call in another control telephone, and so on, and they can call other control or power station P.A.X. telephones at the same station, or neighbouring stations linked by the network.

At generating stations, in addition to direct-wire operational telephone systems between key points, P.A.X. telephones are provided for general internal communication. By dialling into the station's Grid control equipment, the P.A.X. telephones are able to call the G.C.C. telephone operator and also the Divisional Headquarters telephone operator, should the generating station be in a Division with a G.C.C. In the reverse direction, the power station telephone operator receives calls from the control engineers or the G.C.C. and Divisional Headquarters P.A.X. telephones, and dials the required P.A.X. telephone. When the called party answers, the operator extends the incoming call to the P.A.X. by button operation and restores his telephone, but the connection is held and subsequently cleared by the called party. Power station P.A.X. telephones can also call the G.C.C. and Divisional Headquarters over the tie line to the next major station, and can call the control and P.A.X. telephones at neighbouring stations linked by the network. In Divisions without a G.C.C. (Fig. 3) the network is generally arranged so that the power station P.A.X. telephones can dial the local Divisional Headquarters telephone operator direct.

Control telephones at minor stations operate as party-line extensions on the associated major station's control telephone system. Pushbutton calling is provided between the party telephones, with indicators to inform the would-be user when the other party is using the line.

(6.2) Generation and Visual Instructors

On the control desk in the power stations, there is a control telephone and local telemeter indications similar to those telemetered to the G.C.C. of the station's total generation in megawatts 'sent out' and megavars 'gross'. In addition, there is a 270°-scale indicator which responds to the G.C.C. loading engineer's generation instructions with a lamp and alarm to announce the receipt of each fresh instruction. The station engineer acknowledges the instruction by depressing a button which extinguishes the lamp, silences the alarm and sends an acknowledgment signal to the G.C.C. loading engineer. The instruction remains displayed by the pointer until altered by the next instruction.

Also on the control desk are 16 combined lamps and twist buttons for the display and acceptance of visual instructions transmitted by the G.C.C. loading engineer (see Section 5.6) and a button to re-light the last instruction received. Attended transmission stations can, if required, be provided with visual instruction facilities for load reduction and restoration purposes.

(6.3) Limited Selective Control

Unless remotely controlled by the Area Board concerned, unattended minor stations are controlled[6] over the Grid control network by the Generating Board from the associated major stations (Fig. 7), which are usually generating stations and therefore attended. Indications transmitted from a minor station to the G.C.C. via the major station are displayed in the power station control room. Equipment as used to transmit visual instructions to attended minor stations is arranged so that the power station control engineers can select and operate the Generating Board's circuit-breakers at the unattended minor station. Some of the selections are used to reduce and subsequently restore the load at the minor station by selecting lower reference-voltage levels for the automatic equipment controlling the Grid transformer on-load tap-changing gear. Spare selections can be made available to control some of the Area Board's circuit-breakers. The display in the power station of the switchgear indications includes the annunciation of alarms from the switchgear and protection equipment at the minor station, and there may be indications of the Area Board's switchgear as well. Two telemeter signals can be sent from a minor station to the

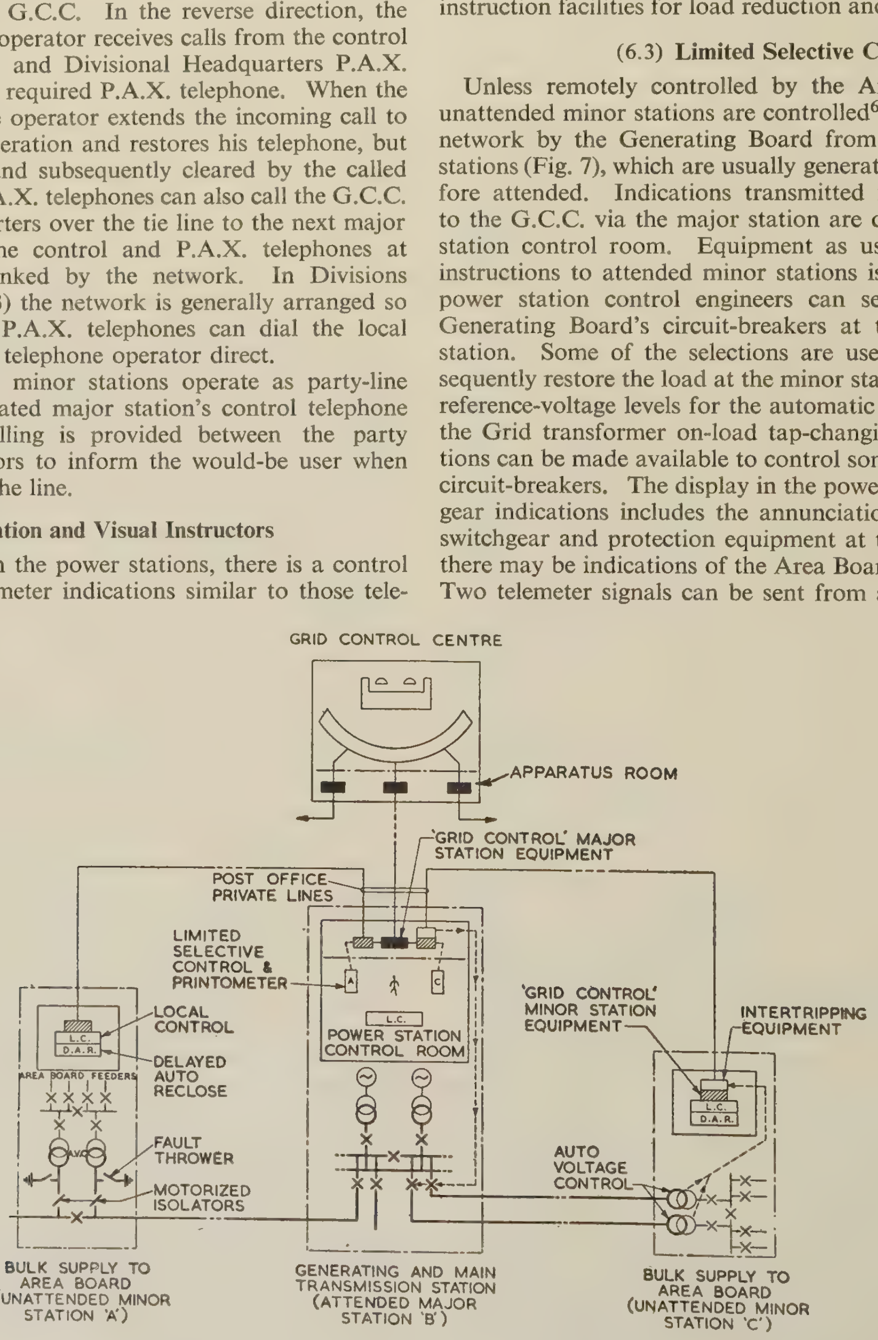


Fig. 7.—Intertripping and limited selective control operating over Grid control network.

major station for retransmission to the G.C.C., but usually one of the signalling ways is used to operate a printer at the major station to record the load at the minor station.

Automatic 2-stage load-shedding equipment can be provided at unattended stations to take effect under fault conditions when generating stations are grossly overloaded and frequency is low.

(6.4) Delayed Automatic Reclosing Equipment

This description of Grid control facilities would be incomplete without some reference to equipment now being provided by the Generating Board at unattended outstations for the delayed automatic reclosing of Grid circuit-breakers after power-line faults or faulty transformers have been automatically isolated from the transmission system. This reclosing equipment was developed by the Authority to accelerate the restoration of bulk supplies and Grid transmission at unattended stations. It can be provided at all types of station, but, so far, it has been installed only at single- and 3-switch 132 kV Grid stations subject to loss of limited selective control due to failure of rented lines. Allowing time for oil recovery in the arc-control devices of the oldest types of Grid circuit-breaker, the 132 kV section switch at the unattended station recloses 15 sec after a Grid line fault to re-energize the line, but only if the line has remained de-energized during that period. On instruction from the G.C.C. the line is then closed at the attended station after system synchronism has been checked. Fifteen seconds after the successful reclosure of the section switch the transformer switch recloses. Switches which trip when being reclosed, or during the next 2 sec, are locked out automatically and prevented from further reclosing. During a shut-down caused by a double-circuit line fault the section switch will reclose 15 sec after either of the power lines has been successfully re-energized from the other end, and in the event of a sustained line fault the line isolator can be arranged to open automatically after an unsuccessful section switch reclosure; the transformer is then put back on load by reclosing the transformer and section switches.

At single-switch 132 kV stations (Fig. 8) a fault on one of the

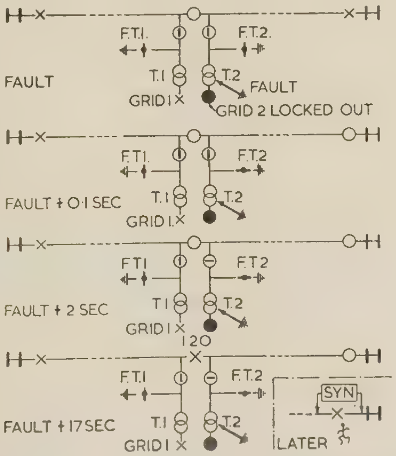


Fig. 8.—Delayed automatic reclosing sequence: transformer fault, single switch station.

Grid transformers trips the Grid section switch and low-voltage transformer circuit-breaker and then trips the remote 132 kV line circuit-breaker by means of a 132 kV fault thrower or by intertripping over a rented line. The transformer isolator then opens automatically, and 15 sec later the Grid section switch recloses to re-energize the line. A recent development automatically substitutes a spare transformer common to the station for the faulty one before reclosing the section switch.

Where two unattended stations with automatic reclosing equipment are in tandem on the same 132 kV system, the section switch at one station is arranged for dead-line charging, but the other section switch will only reclose after the affected power line has been successfully re-energized either from the dead-line charging station or from the attended station, as the case may be, and then only when both lines are alive and the systems are in synchronism.

(7) INTERTRIPPING

(7.1) C.E.B. Practice

Intertripping between Grid stations over the control networks was first introduced in 1934 in the Bristol and Manchester Grid control areas. The original systems were low-speed (0·8 sec) with coded impulse signalling, one using d.c. and the other v.f. transmission. The v.f. system was employed in regions where the distance protection equipment could not be expected to operate at all times on account of the marginal difference between load and fault currents. The coded signals were transmitted to the G.C.C. and there relayed to the required stations. Depending upon their location in the control areas, stations 20 miles or so apart intertripped each other over circuit mileages totalling as much as 300 miles for stations in Devon and Cornwall. With the concentration of intertripping at the G.C.C. the v.f. system, in principle, was more vulnerable than the d.c. system, but its 6 codes made it the only system able to cater for the many multi-ended feeders that appeared during the post-war development of the Grid. The d.c. system was generally used on transformer feeders between h.v. and l.v. stations to intertrip the h.v. switches on the incidence of transformer and l.v. faults; it was superimposed on the Grid control line between the stations.

(7.2) C.E.A. Practice

A pool of transportable intertripping equipment was created in 1950 to cater for expansion of the Grid systems, including many temporary stages of construction. Intertripping applications were considerably reduced when the use of automatic 132 kV fault throwers to clear transformer and l.v. faults was approved subject to the fault level not exceeding 1 500 MVA. However, intertripping was still required for the following conditions:

(*a*) At teed or feeder transformer stations where the fault level exceeded 1 500 MVA after the local switches had tripped.

(*b*) At teed or feeder transformer stations where there could normally be an in-feed to the Grid.

(*c*) At any station, irrespective of the type of protection employed, where there was insufficient fault current to operate the protective equipment at the remote end.

Because the low-speed intertripping systems took almost a second to transmit the coded trip signals, they were superseded by a 0·35 sec coded v.f. system which was suitable for any number of multi-ended feeders and could be superimposed on the standardized system.

High-speed (100 millisec) intertripping systems have been in operation at a number of stations during the last 5 years, although not on the Grid control networks, because they normally require the continuous use of several v.f. signalling channels. In one system a signal of frequency f_1 is transmitted continuously and is a convenient means of channel supervision. At the instant of intertrip this frequency is disconnected and a signal of frequency f_2 is transmitted continuously. In another system which caters for two circuit-breakers, f_1 and f_2 are transmitted normally. At the instant of intertrip to trip circuit-breaker No. 1 a third frequency f_3 is transmitted in place of f_1, and to trip circuit breaker No. 2 f_3 is transmitted in place of f_2.

In Great Britain there are not many installations for intertripping by power-line carrier because it has not been certain that carrier signals can be transmitted through a power-line phase fault. Such installations as exist are primarily intended for transformer faults.

(8) FUTURE DEVELOPMENTS

(8.1) Protection

A signalling system operating over the Grid control networks is being developed to provide accelerated tripping and interlocked tripping facilities. An above-speech v.f. signal is transmitted for 2 sec from the station where the feeder circuit-breaker trips in first-zone time. The reception of this signal at the station or stations where the first-zone protection is ineffective causes the second-zone protection to be accelerated. A similar arrangement is being developed so that fault throwers may be employed on single- or multi-ended transformer feeders having l.v. in-feeds. The reception of the signal from the h.v. station will unlock inhibited directional overcurrent relays at the transformer stations to trip the transformer l.v. circuit-breakers associated with the faulty line.

(8.2) Automatic Frequency Control

Automatic frequency control makes it possible for independently operated networks to be interconnected and for power exchange contracts to be arranged. Each network must generate at all times its own requirements with the agreed power transfer and contribute its share of assistance in maintaining the declared system frequency. Automatic frequency control was being considered by the Authority, but, although it has now been decided to provide a d.c. interconnection with France instead of an a.c. link, it is foreseen that automatic frequency control with tie-line bias has possibilities on the British Grid so that maximum use may be made of transmission. To meet this eventuality a system of frequency control which was tried out experimentally when a.c. transmission with France was under consideration is being developed as a possible future provision to be integrated with the standardized system.

(9) ACKNOWLEDGMENTS

The author wishes to thank the Central Electricity Generating Board for permission to present the paper.

The success of a country-wide project depends on the active co-operation of many groups and individuals, and the paper affords an opportunity to acknowledge the co-operation received from the manufacturers, the Inland Telecommunication and Engineering Departments of the Post Office and the many departments within the Central Electricity Generating Board both at Headquarters and in the Divisions, who were concerned with the work described.

On behalf of the Technical Committee the author would also like to thank Mr. F. J. Lane, then Deputy Chief Engineer (Transmission), for his confidence and support, particularly during the early stages of the project, and to acknowledge the guidance given by Mr. P. J. Squire, who until early 1957 was the Central Authority's System Operation Engineer.

(10) REFERENCES

(1) Burns, G. A., and Rayner, T. R.: 'Remote Control of Power Networks', *Journal I.E.E.*, 1936 (**79**, p. 95).

(2) Peattie, J. D.: 'Control Rooms and Control Equipment of the Grid System', *ibid.*, 1937 (**81**, p. 607).

(3) Forrest, J. S.: 'Thunderstorm Recording', *Weather*, 1946, **1**, p. 148.

(4) Cooper, A. R.: 'Load Dispatching and the Reasons for it, with special reference to the British Grid System', *Journal I.E.E.*, 1948, **95**, Part II, p. 713.

(5) Dunn, R. H., and Chambers, C. H.: 'Telemetering for System Operation', *Proceedings I.E.E.*, Paper No. 1400 M, October, 1952 (**100**, Part I, p. 39).

(6) Casson, W., and Gunning, P. F.: 'Methods and Channels for Control and Intertripping used on the British Grid System', C.I.G.R.É., Paris, 1956, Paper No. 307.

(7) Burns, G. A., Fletcher, F., Chambers, C. H., and Gunning, P. F.: 'The Development of Communication, Indication and Telemetering Equipment for the British Grid' (see next page).

(11) APPENDIX

Table 1 shows the size, population and megawatt capacity of the various Grid control areas, and lists the principal features of the control networks as at May, 1958.

Table 1

GRID CONTROL AREAS AND EQUIPMENT INSTALLED (MAY, 1958)

Control area	Area in square miles	Population, approx. thousands	Capacity (sent out MW) 1.1.58	Major stations	Minor stations	Telemeters	Circuit-breaker indications	Overload indications	Generation instructors	Visual message instructors	Post Office lines	Private pilots
Thames North (Eastern Division and part of London Division)	7856	6907	3158	21	22	137	471	79	19	22	43	29
Thames South (South Eastern Division and part of London Division)	3335	7058	3357	23	8	160	515	69	20	24	48	31
Bristol (Southern, South Wales and South Western Divisions)	17218	7871	3305	31	35	150	535	75	26	31	91	13
Birmingham (Midlands and East Midlands Divisions)	10372	7521	4316	28	26	233	534	67	32	27	81	40
Leeds (Yorkshire Division) ..	5344	4656	2802	22	16	115	283	52	19	20	46	8
Manchester (North West, Merseyside and North Wales Division)	6838	6980	3771	29	19	193	420	48	24	25	90	23
Newcastle (North Eastern and Part of North West, Merseyside and North Wales Division)	7384	3158	1536	15	11	89	309	18	13	13	34	11
Totals	58347	44151	22245	169	137	1077	3067	408	153	162	433	155

[The discussion on the above paper will be found on page 574.]

621.398 : 621.311-1

The Institution of Electrical Engineers
Paper No. 2627 S
May 1958
©

THE DEVELOPMENT OF COMMUNICATION, INDICATION AND TELEMETERING EQUIPMENT FOR THE BRITISH GRID

By G. A. BURNS, F. FLETCHER, M.B.E., C. H. CHAMBERS, Associate, and P. F. GUNNING.

(*The paper was first received* 12*th October*, 1957, *and in revised form* 18*th February*, 1958. *It was published in May*, 1958, *and was read before the* Supply Section 28*th May*, 1958.)

SUMMARY

The development of a 'standardized system' of communication, indication and telemetering to control the British Grid was started in 1949 by certain telephone manufacturers and the then British Electricity Authority. The system is now in full operation in all Grid control areas of the Central Electricity Generating Board. The paper explains some of its design features. The facilities and services it affords are described in the companion paper.[6]

The methods employed in transmitting general indications and instructions over the rented Grid control networks, between Grid Control Centres and stations in the control areas, are explained, and the paper shows how group working is catered for by satellite and minor-station equipment and how unattended minor stations are controlled from associated major stations.

The design of the telephone system, which caters for administration as well as Grid control traffic, is explained in some detail, as also is the telemetering system with its initiating devices, miscellaneous instruments and arrangements for telemeter summation and retransmission. The paper concludes with a description of power supplies, testing facilities, alarms and general equipment.

(1) INTRODUCTION

(1.1) General

In 1949 the British Electricity Authority invited the telephone manufacturers who had equipped the Grid control areas since 1932 and were experienced in the design of Grid control equipment* to co-operate with the Authority in the development of a standardized but readily extensible system of communication, indication and telemetering. Throughout the country all generating stations, transmitting stations and Grid Control Centres operated by the Authority were to be re-equipped with the new system.

(1.2) Telecommunications Technical Committee

The approach resulted[6] in the setting-up of a joint Telecommunications Technical Committee (T.T.C.) which in the interests of standardization decided:

(*a*) To use P.O.-type relays and switches, and jack-in P.O. 3000 type mounting wherever practicable, even for electronic equipment.

(*b*) That equipment in the apparatus rooms of Grid Control Centres (G.C.C.'s) should be jacked into open-type telephone exchange racks.

(*c*) That equipment at the outstations (i.e. power stations and Grid stations) should be jacked into racks enclosed by dust-proof cubicles of uniform appearance, arranged for top and bottom cable entry. It was not necessary for them to match the appearance and finish of control panels and protection cubicles, since the standardized system was to be installed in separate rooms (telecommunication apparatus rooms) at the outstations.

* Automatic Telephone and Electric Co. Ltd., General Electric Company Ltd. and Standard Telephones and Cables Ltd.

Mr. Burns is with the Automatic Telephone and Electric Co. Ltd.
Mr. Fletcher is with the General Electric Co. Ltd.
Mr. Chambers was formerly with Standard Telephones and Cables Ltd.
Mr. Gunning is with the Central Electricity Generating Board.

(1.3) Original Conception of Standardized System

Communication, of paramount importance in an emergency, was to be independent of indicating and telemetering equipment. In the initial development of the new system, telephone calling was by means of a voice-frequency (v.f.) signal in the speech band with a different impulsing rhythm for each telephone.

Indications and telemeter signals were to be transmitted by 12-way time-division multiplex transmitters on a separate v.f. channel above the speech band, at 50 bauds, each complete cycle being repeated 3 times/sec continuously. Two of the 12 ways were to be mark and space pulses in a low-speed indication train; the other 10 ways were to scan induction-type telemeter impulse meters.

This system was abandoned when it was realized that, when working into a group of stations, (*a*) there would be insufficient impulsing rhythms to call each telephone selectively, and (*b*) high-performance lines and complicated electronic equipment would be required for small stations having few indications and no telemetering.

(1.4) The Standardized System

A less complicated system was adopted using ordinary-grade Post Office lines with:

(*a*) D.C. signalling, or alternatively 300 c/s signalling with 400 c/s high-pass speech transmission, for the infrequent transmission of general indications, visual instructions and telephone calls (Fig. 1).

(*b*) Above-speech v.f. signalling for high-density telemetering traffic using time-division multiplex 50-baud transmission for 10 continuous readings on single channels of 120 c/s bandwidth.

(*c*) Not more than 4 major stations in a group, where group working was required, and with 3 of the stations as direct satellites on the parent station, which would have a line to the G.C.C. (Fig. 2).

(*d*) Simple telephone and indicating equipment for small (minor) stations as extensions on nearby major stations (radial, parent or satellite) and a simple telemetering system for stations from which there may be only one or two telemeter transmissions.

(*e*) Communication between stations in a group, and this to be overridden by calls to and from the Grid control engineers.

(*f*) Tie lines between major stations served by separate lines to the G.C.C., as alternative communication routes thereto, should either of the direct routes be engaged or out of order.

Fig. 1.—Telephony and line signalling at outstations.

* Provided only at stations where rise of earth potential can exceed 430 volts (r.m.s.).

(*g*) Non-priority communication facilities for administration purposes over the Grid control network between the private automatic exchanges (P.A.X.'s) at power stations, the G.C.C., the associated Divisional Headquarters and other stations in the control area.

(*h*) Non-priority communication facilities over the Grid control network independent of the G.C.C. operator, for P.A.X. telephones at Divisional Headquarters.

(*j*) Control of unattended minor stations from the associated major stations.

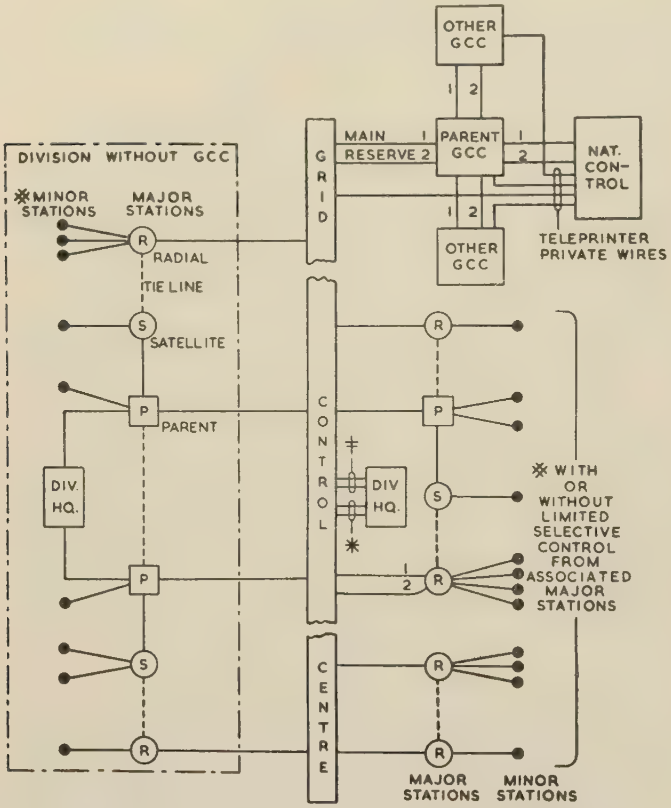


Fig. 2.—Typical communication network for a Grid control area.

Transmission loss (including G.C.C. and station equipment) not to exceed 20 dB between G.C.C. and major stations, or 25 dB to major stations over tie lines or to minor stations over direct routes.
‡ Low-loss junctions for automatic communication with stations in Division.
⁎ Inter-P.A.X. junctions.

(2) LINE SIGNALLING

(2.1) Direct-Current Signalling

Post Office lines between stations and G.C.C.'s vary in length up to 150 miles, but the average line is short enough for d.c. signalling, and provided that other circuits are not affected, permission to employ earth-return signalling is usually forthcoming. Earth-return d.c. phantom signalling is inexpensive and it does not interfere with speech or above-speech v.f. telemeter signalling, nor is it affected by line reversal, and at stations where isolation is not required it permits the use of the earthed-positive 50-volt station batteries for line signalling. The use of earthed station batteries for earth-return signalling precludes the polarizing of train marking impulses. Instead, pulses are marked by increasing the make period from 50 to 160 millisec. Unmarked pulses are transmitted at 10 a second with equal make and break periods.

The Authority was relieved of the necessity to provide isolation between rented lines and terminal-station earths when the rise of earth potential under maximum fault conditions did not exceed 430 volts r.m.s.; but isolation to 2 kV r.m.s. (1 min) had to be provided if the rise of potential exceeded 430 volts, and to 5 kV r.m.s. (1 min) if it reached 1 000 volts r.m.s. Even though many stations do not require isolation, the standardized system provides 2 kV isolation at all stations, but it is short-circuited when use is made of the earthed station battery (Fig. 1).

For each rented line at the outstations a standard wall-mounted cabinet is provided, with accommodation for an isolated dry battery, should this be required, for isolation transformers, d.c. line-signal milliammeter and an isolated jack-in relay set to suit the line service (G.C.C., parent, satellite, tie-line, minor, etc.). Routine tests of line insulation and continuity, and of the battery when fitted, can be made from test jacks on the line cabinets using a simple test set mounted alongside, comprising a voltmeter, battery and test cord.

Only on tie lines between major stations is d.c. loop signalling used and then only as a priority signal from the G.C.C. control engineers to override any d.c. earth dialling or call holding in progress between the stations.

(2.2) Voice-Frequency Signalling

On lines where d.c. earth-return signalling could not be used the well-established practice of using 300 c/s tone signalling with the speech band restricted at the lower end to 400 c/s was retained, with 480 c/s suitably interrupted for the ringing and busy tones.

With many years' experience of 400–2 000 c/s band-pass speech transmission for Grid control telephony, it was decided to continue the practice. This permitted the provision of 120 c/s bandwidth telemeter signalling channels at 2 220 and 2 340 c/s for transmission simultaneously with speech on lines unsuitable for transmission above 2 400 c/s.

Fifty-volt battery-energized voice-frequency receivers, oscillators and amplifiers were developed to meet the requirement that Grid control should be independent of the power system. The receivers are suitable for use up to 15 pulses/sec. Amplifiers in the speech-band circuits compensate for filter and transmission loss. Amplifiers are also provided at parent stations for the by-passed telemeter signals from satellite stations to the G.C.C. By appropriate internal strapping, the oscillators can operate at 300, 2 220 or 2 340 c/s. Receivers at the G.C.C. for 50-baud telemeter signals are energized from the mains and from the standby Diesel-alternator (see Section 8.3).

The following filters were developed to suit any arrangement of v.f. signalling used in the standardized system:

(*a*) Physically combined 400 c/s high-pass and low-pass filters to separate 300 c/s tone signalling from speech.

(*b*) 2 000 c/s low-pass filters to remove speech frequencies which would otherwise interfere with telemetering.

(*c*) 2 220 and 2 340 c/s band-pass (120 c/s) filters for telemeter signalling to make the untuned receivers frequency-selective, to match lines to oscillators and receivers and to improve the waveshape of oscillators. Other band-pass filters (and oscillators) were developed for 2 460, 2 580, 2 700 and 2 820 c/s channels superimposed on the control network for inter-tripping and system protection,[6] and for the largest stations from which more than 2 telemetering channels were required. 300 c/s signalling is used on lines from parent stations to satellite stations and to the G.C.C. to minimize impulse distortion on trains relayed by parent stations, and because inter-station dialling between parent and satellite stations requires the available d.c. channels.

(3) GENERAL INDICATIONS AND INSTRUCTIONS

(3.1) Common-Channel Signalling

Impulse trains are transmitted on the d.c., or 300 c/s v.f., signalling channels (Fig. 3) for the following purposes:

(*a*) From the G.C.C. to select visual message or generation instructions at the stations.

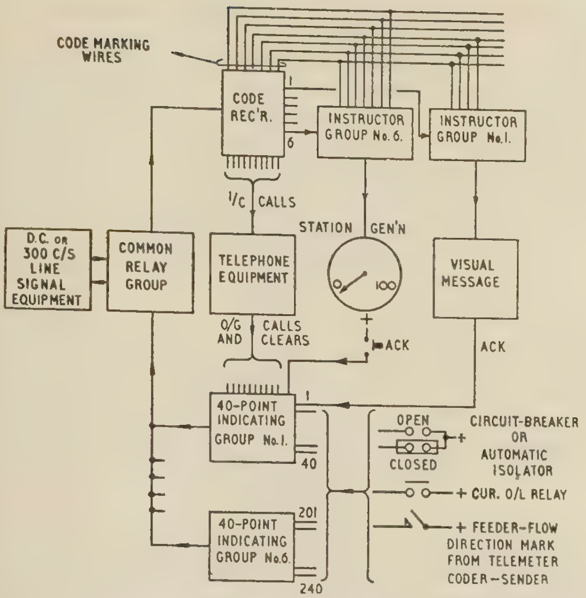


Fig. 3.—General signalling scheme at stations for indications, instructions and telephones.

(*b*) From the stations for the indication at the G.C.C. of circuit-breakers, automatic isolators, overloaded feeders, direction (import or export) of telemetered transfers, loss of telemeter channels between stations and acknowledgment of visual message instructions.

(*c*) For telephone calling and clearing, generation instruction acknowledgment and check indication request. Short trains of unmarked impulses are transmitted, the number of impulses varying according to the telephone called or facility signalled.

To prevent lock-out due to channel congestion during heavy traffic, the selection, indication and telephone trains use the common signalling channel in turn.

(3.2) Selection Trains (Radial Stations)

Binary coding is used for selection from the G.C.C., each variable in the code consisting of a pair of complementary pulses—long and short or short and long. This precaution is used primarily to check the cam-operated change-over contacts on such mechanical transmitters as the generation instructors (Section 7.4). The proof of selection is based on fixed-quantity checking and the fact that all pulses are complementary in pairs. A confirmatory (O.K.) signal is then transmitted to the G.C.C., signifying that the selection train has been correctly received. The selection train selects any one of a total of 6 instructors, generation or visual-message, by means of a 4-pulse code in which any 2 pulses are marked. Binary coding 2^7 caters for the 100-point generation instructions and binary coding 2^4 for 16-way message instructors.

(3.3) Indication Trains (Radial Stations)

The capacity of the indicating equipment at the G.C.C. for each line is 240 points in 6 groups of 40. Each indicating train for 40 points consists of a start pulse, a 4-pulse group selection code and a marking pulse to steer the ensuing 40 pulses through a distributor switch to the point-indication relays. If this pulse were not marked it would mean that a short train was being received, in which case the distributor would switch the ensuing pulses to the telephone calling equipment [see Section 3.1(*c*)]. The 4-pulse group-selection code contains 2 marked pulses to give the 6 group selections.

A confirmatory (O.K.) pulse is sent from the G.C.C. when it has received precisely the fixed number of pulses comprising an indication train. Indication trains are repeated if no O.K. pulse is received from the G.C.C., but after two unsuccessful repetitions the station stops transmitting.

In general, two consecutive pulses, one marked and one unmarked, are required for each circuit-breaker indication. This is an improvement on single-point indication in which 'absence of close implies open', giving false indications when circuit-breaker auxiliary contacts are faulty. With 2-point indication any of four conditions can be signalled, so that should both pulses be marked or unmarked the circuit-breaker discrepancy lamp on the mosaic diagram at the G.C.C. lights continuously, irrespective of the semaphore position, and there is no audible alarm.

To start the indication train a relay is provided for each pair of indicating points. This start relay caters for one circuit-breaker or two telemeter direction signals (Section 6.2), or one direction signal and one overload signal, but not for two overload signals, because these may be initiated at the same instant without response from the common start relay, which is differentially connected.

At the G.C.C. all the indication relays in the group selected by the group code are released without affecting the dead-face mosaic switching diagram. The indication relays then re-operate according to the 40 indication pulses and remain operated if the train is correctly received. Any indication then 'in discrepancy' will flash and give the alarm.

When the switching engineer sends a check request signal [Section 3.1(*c*)] the indication relays release to light the discrepancy lamps until the start of the indication train. This serves as a lamp test.

(3.4) Indication Trains (Parent and Satellite Stations)

The capacity of the indicating system is not increased for parent satellite operation but remains at 240 points as for a radial station. This is intentional so that it restricts the number of large stations in a group of stations served by one line to the G.C.C. When an indication train is transmitted from one of the satellite stations it is relayed impulse by impulse to the G.C.C. by the parent station; meanwhile the parent station cannot send an indication train, and by transmitting a channel-busy indication it also prevents the satellite stations from doing so.

(3.5) Selection Trains (Parent and Satellite Stations)

With an additional 4-pulse group-selection code containing 2 marked pulses, the capacity of the selection system from the G.C.C. is increased from 1 to 6 stations, but as it would be imprudent to have so many stations depending upon one line the number is restricted to 4. Reception of the additional group-selection code at the parent station causes it to relay the subsequent selection pulses into the local equipment or to the selected satellite station.

(4) THE TELEPHONE SYSTEM

(4.1) Principles

The telephone system, which uses the common channel (Section 3.1) to set up calls, is arranged (Fig. 4) to satisfy the following requirements:

(*a*) At the stations, 'control telephones' are called with a minimum of pulses, one per telephone.

(*b*) During conversation, the common channel is not held but the control telephone holds itself connected to the line. This leaves the channel free for subsequent priority calls, selections

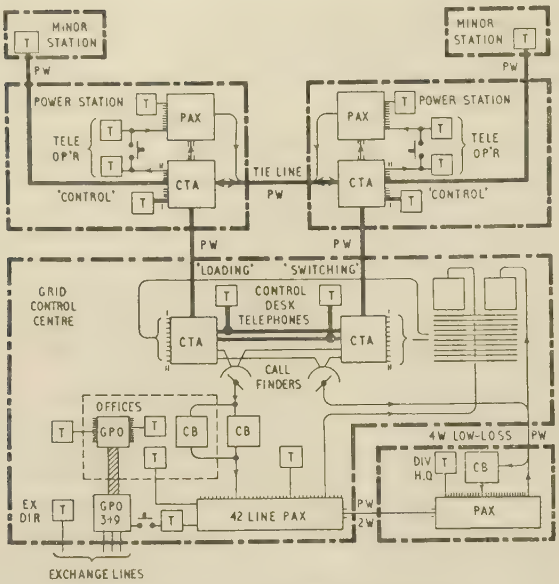


Fig. 4.—General telephone schematic.

T—Telephones.
PAX—Private automatic exchange.
CB—Cordless telephone board.
CTA—Control telephone apparatus.

and indication; but it requires calls from the G.C.C. to be held until the called party answers or until a self-resetting time relay operates.

(*c*) The well-established practice of providing the control desks with direct key calling and answering and visual indication of incoming calling and busy conditions is retained. Control engineers are not dependent on directories or operators.

(*d*) Overriding priority calling is available between G.C.C. control desks and the outstation control telephones.

(*e*) Access to P.A.X. extensions at generating stations is provided by the station operators. These extensions, as well as the control telephones, have automatic access to the G.C.C. and Divisional Headquarters telephone operators for extension to the local P.A.X. telephones.

(*f*) A simple code is sent at the conclusion of a call to the G.C.C. so that connections set up by the G.C.C. or Divisional Headquarters telephone operators may be cleared.

At major stations, each control telephone is provided with a connector switch with which the user, by dialling, can set up calls independently of the other control telephones. On engaged calls, the user receives busy tone until he hangs up, but on calls to the control engineers he can, if his call is sufficiently urgent, exercise priority by dialling an extra digit. Priority calls automatically disconnect established non-priority parties, who then receive busy tone. Priority calls do not disconnect control engineers' conversations; from radial stations they are allowed to intrude, the control engineer being made aware by having to answer the calling lamp. The Grid control engineers can call control telephones, even though the required telephone is engaged or the hand-set off the rest, and can throw off unwanted control telephones by subsequent telephone selection.

(4.2) Parent-Satellite Working

In a parent-satellite group (Fig. 2), calls from the G.C.C. contain selecting information to steer the call at the parent station to the required station, parent or satellite. This routes the call to the correct destination but it does not switch the speech circuits at the parent station. This is done, after the 300 c/s telephone selection, by a 2220 c/s signal train to position a speech-switching selector at the parent station.

Calls from telephones at a parent or satellite station annunciate themselves as lamp signals to the control engineers but do not control the speech-switching selector at the parent station. Until the control engineer answers, the callers receive ringing tone from the parent station. Should the control engineer be talking to another station in the same group, a caller will receive busy tone from the parent station and his call will not be annunciated. If the call is from a control telephone, the caller may choose to exercise the priority facility. This call will then be annunciated and the tone signal from the parent station will change from busy to calling, but the speech-switching selector at the parent station will only be set in the caller's favour by the control engineer when he answers the call.

This arrangement was adopted for group working to prevent groups of stations being tied up as the result of stations not clearing; by its means the Grid control engineer always maintains control over the group of stations.

(4.3) Inter-Station Dialling

Earth-phantom d.c. dialling is provided between all stations in a group for both control telephones and power station P.A.X. telephones. Calls from the G.C.C. take priority, and when conversations are interrupted the unwanted telephones receive busy tone.

(4.4) Tie Lines

Tie lines between pairs of major stations (Fig. 2) provide standby communication should a direct line fail, and provision is made to enable the control engineers to call one selected telephone at either major station via the other major station. The tie lines are also used for inter-station calls from control telephones and power station P.A.X. telephones. Inter-station calls are received on a control telephone connector to call the local P.A.X. or control telephones, or to call the G.C.C. or Divisional Headquarters, or to seize outgoing lines to other stations. Earth-phantom signalling is used for inter-station calling and supervision. Loop d.c. is used as a priority calling condition overriding all other traffic, but because of the automatic disconnection of line conversations with this type of call, it is used solely by the control engineers at the G.C.C. and not by the office staff there or at the Divisional Headquarters.

When a control engineer calls a major station through another major station over a tie line, a loop d.c. impulse is transmitted to the called station which returns an earth-phantom d.c. condition to hold the tandem station until the call is subsequently cleared or a self-resetting time relay operates at the called station.

(4.5) Office Telephones at Grid Control Centres and Associated Divisional Headquarters

The G.C.C. office staff use a 42-line P.A.X. for local services and for connection to

(*a*) Divisional Headquarters P.A.X. and telephone operator;
(*b*) P.A.X.'s at important stations served by reserve lines;
(*c*) P.A.X.'s at other G.C.C.'s and the exchange at National Control, using the national network;
(*d*) 200-point 2-motion switches (network connectors) to make selections to call any control telephone or power station P.A.X. telephone operator in the control area.

The office staff at the associated Divisional Headquarters use the local P.A.X. for connection to the P.A.X. and telephone operator at the G.C.C., and thereby have the same facilities as the G.C.C. staff. Over low-loss junctions to the G.C.C. provided for the purpose, they are also able to make selections to

control telephones and telephone operators at stations in the Division.

Calls from stations for the G.C.C. office staff are first decoded at the G.C.C. and switches automatically find the calling station equipments to extend them to cordless boards, where the operator (by day) or clerk (by night) answers the calls, dials the required P.A.X. extensions and connects the parties. These connections are automatically released by the station clearing signals [see Section 4.1(*f*)]. Busy tone is returned to the caller should all cordless-board circuits be engaged.

Calls from stations for the Divisional Headquarters staff are decoded at the G.C.C. and switches automatically find the affected station equipments to extend them by means of d.c. earth signals over disengaged 4-wire junctions to the Divisional Headquarters cordless board, where the operator answers the calls, dials the required P.A.X. extensions and connects the parties. The connections are automatically released by the station clearing signals. Busy tone is returned to the caller should all 4-wire junctions be engaged.

Control engineers can listen-in on all conversations with out-stations and, if necessary, can throw off P.A.X. telephones by switching direct current onto the speech circuit. This operates a cut-off relay in the particular network connector on outgoing calls, or, on incoming calls, releases the particular G.C.C. or Divisional Headquarters cordless-board circuit. The station party is thrown off by the subsequent telephone selection made by the control engineer. Telephones that have been disconnected from conversations as a result of priority calls receive busy tone until restored.

(4.6) Power Station P.A.X.'s and Operators

Calls from the G.C.C. to power station telephone operators are extended by the operators into the station P.A.X.'s, the speech connections being held by the called parties, normally by the station P.A.X. When the station P.A.X. cannot provide the latter facility a 'call-holding' connector is provided. This also responds to the operator's dialling and holds the call until its testing circuits show that the called telephone has cleared.

Power station P.A.X. extensions can call the G.C.C. and Divisional Headquarters telephone operators either direct or via other major stations linked by the network, and can call the control and P.A.X. telephones at those stations.

(4.7) Speech Levels

To ensure that speech levels are always satisfactory despite the complications of group working, the overall transmission losses must not exceed

(*a*) 20 dB between G.C.C. telephones and control telephones at major stations over direct routes;
(*b*) 25 dB if the routes include a tie line;
(*c*) 25 dB over direct routes to minor stations.

This requirement determines the choice between 2- and 4-wire lines for the various links. 4-wire speech switching is provided at the G.C.C. on calls between the Divisional Headquarters and 4-wire stations, and also at parent stations on calls between the G.C.C. and 4-wire satellite stations. To avoid complications that would otherwise arise, the extra loss at major stations of 2-wire switching of 4-wire lines to minor stations has been accepted.

(5) MINOR SYSTEM

(5.1) Principles

The standardized system includes minor-station equipment to cater for small Grid stations in the following way:

(*a*) Minor stations are extensions on nearby major stations (radial, parent or satellite); they use d.c. phantom earth-return signalling for telephone calling and circuit-breaker indications.

(*b*) Minor-station control telephones are arranged as party telephones dialling into a control telephone connector at the major station.

(*c*) Minor-station indication trains are decoded and stored at the major stations for retransmission to the G.C.C. by the major stations' indication equipment.

The minor station transmits heavy-current signals for the indication train and light-current signals for dialling and call answering. When dialling, the current is reversed between impulses to discharge the line and reduce impulse distortion; this is the only instance in the standardized system where polarized impulsing is provided, and it requires a primary battery at the minor station. The major station transmits a heavy-current impulse as an indication-train request signal for check purposes and also as an indication-train 'received O.K.' signal. The major station selectively calls the minor station's party telephones by means of 2 light-current impulses for party A and by a light-current impulse followed by a heavy-current impulse for party B. Pushbutton calling is provided between the party telephones, and indicators on each show when the line is engaged.

When required, the visual message instructor is added to the minor system. The instruction selection from the G.C.C. is first decoded at the major station and then coded to suit the minor system. It is then transmitted by 300 c/s signalling to the attended minor station, where the proof of selection is based on fixed-quantity check and the fact that the pairs of coded pulses are complementary in marking. The instruction acknowledgment signal is a marked point in the minor station's indication train.

(5.2) Limited Selective Control

Facilities can be provided at major stations for the remote control of circuit-breakers or other devices in the associated unattended minor stations. At the major station a control panel controls the transmission of the 16 message selections to the minor station and 32 control operations are made available by the additional transmission of a 5-pulse 'open' or 'close' code to qualify the 16 selections (Fig. 5). The positions of the controlled devices are indicated at the major station as well as being transmitted, if required, to the G.C.C.

At the minor station the 16-message decoder selects the circuit-breaker interposing relays and energizes the one selected by the 'open' or 'close' code for 2 sec as timed by 10 marked pulses transmitted as a suffix to the selection train or, if required, for as long as the trip or 'close' button is operated at the major station. A request-check facility is provided which exercises the v.f. selection and d.c. indication equipment.

(6) TELEMETERING

(6.1) Multiplex Telemetering

With the demand for more telemeters in the 1940's, telemetering systems which monopolized a valuable signalling channel for each telemeter were superseded by multiplex systems catering for a number of telemeters on one signalling channel. The new systems served their purpose, but it was evident that telephone relays were not satisfactory for continuous multiplex operation.

In 1946, an electronic multiplex telemetering system was produced which transmitted a different teleprinter character code for each kWh-meter impulse. The impulses were separately stored until the appropriate code was transmitted by a coder

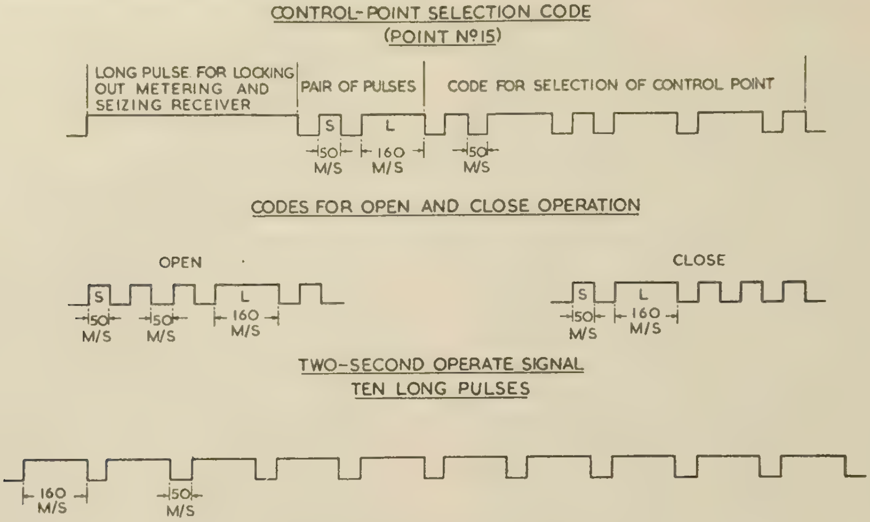


Fig. 5.—Limited selective control: train of pulses.

sender. The different codes were decoded at the G.C.C. and reproductions of the originating kWh-meter impulses were distributed to the respective telemeter receivers. Apart from telegraph relays for transmitting and receiving, the equipment was all-electronic, using cold-cathode tubes for impulse counting and gating and stabilized multivibrators for pulse generation. The telemeter receivers were also electronic and produced a direct voltage in proportion to the kWh-meter impulse rate. A development of this electronic multiplex system was designed for the standardized system. Instead of transmitting teleprinter character codes, start-stop time-division with 20 millisec marking was adopted, such that 10 meters were scanned in 200 millisec 3 times/sec. These multiplex systems were described by Dunn and Chambers[4] in 1953.

(6.2) 10-way Coder-Senders and Decoders

The 10-way coder-sender is a self-contained jack-in group comprising the electronic equipment, a power pack and a pair of relays for each of the 10 associated impulse meters (Fig. 6). The relays are released differentially to ensure that the contacts of the impulse meters do not have to break current and that the relays are speedily released on the shortest of pulses when the meters are rotating at maximum speed (Fig. 7). One relay operates and restores with each rotation of the meter to mark the appropriate way on the electronic time scan. The other relay operates during reverse rotation of the impulse meter on power flow away from the station to mark the corresponding direction point in an indication train. The occasional loss of a meter impulse or the addition of a spurious impulse in an impulse-rate telemetering system is not serious so long as the occurrence is infrequent, whereas the correct indication of power-flow direction is at all times most important; it was therefore decided that direction intelligence should be transmitted in the general indicating system as a point indication [see Section 3.1(*b*)]. This allowed the full capacity of the multiplex system to be available for telemetering.

The code-sender has a static tone-keying circuit. The correct ionization level for the cold-cathode tubes is provided by lamps continuously alight under the group covers of the coder-senders and decoders. A synchronizing check signal is continually sent by the coder-sender, which alternately marks and spaces an 11th dummy telemeter position on successive scans. To prevent the decoder locking out of synchronism to static signal patterns, the coder-sender inserts a 240 millisec pause after every second

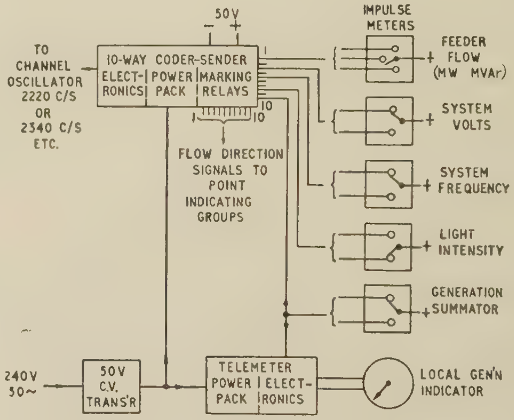


Fig. 6.—Station telemetering.

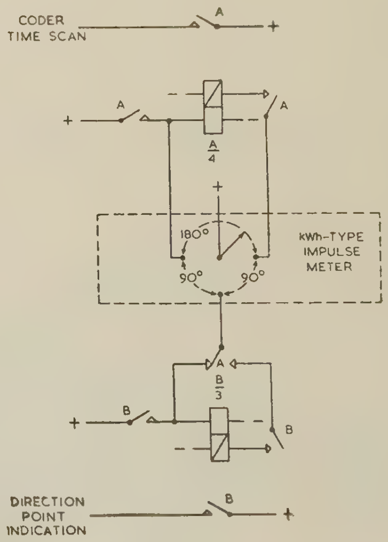


Fig. 7.—Feeder-flow meter impulse circuit.

train, to make sure the decoder scan at the G.C.C. is completed before the start of the next coder-sender scan.

The decoder has a v.f. receiver and telegraph relay which

respond to the 50-baud telemeter signals, and 12 side-stable telegraph relays as follows:

(*a*) One for each telemeter. These relays operate and release on their respective mark and space signals and impulse the associated telemeter groups (Section 6.4).

(*b*) Two for check synchronism. These relays flip-flop with alternate trains; one is controlled locally while the other is controlled by the alternate mark-space signals corresponding to the 11th dummy telemeter time-scan. Should this alternation cease, a corridor circuit is completed by the two relays to light the associated 10 telemeter out-of-order lamps (Section 6.6).

Time-division multiplex transmission tends to produce cyclic distortion of regular impulsing but not sufficiently to affect the telemeters.

(6.3) 2-way Coder-Senders and Decoders

For stations from which not more than two telemetered readings are required, a simple relay system was produced based on the transmission of a 45 millisec impulse for telemeter No. 1 and a 90 millisec signal for telemeter No. 2. To economize in channels to the G.C.C. this 2-way telemetering system is frequently employed from one station to another, where the signals are decoded and then patched into the receiving station's 10-way sender for retransmission to the G.C.C. This system is also used from unattended minor stations to transmit 300 c/s impulses to operate printers at major stations.

(6.4) Telemeters

All telemeter indications in the standardized system are covered by four standard telemeters accurate to within 1% of full scale. As their performance is asymptotic the response time is defined as the time taken to indicate 80% of a change in reading. The individual types produce full-scale deflection for impulse rates as follows:

(*a*) Type 1.—66⅔ impulses/min for active-power feeder-flow indications, with a response time of 15 sec. 66⅔ impulses/min represents 100 MW for 25 kWh impulses. The impulse value is increased in proportion for telemeter scales of 200, 300 MW, etc. To eliminate pointer wobble at low impulse rates this telemeter has a long time-constant which is only effective on steady readings.

(*b*) Type 2.—33⅓ impulses/min for reactive-power feeder-flow indications with a response time of 30 sec. The rate represents 50 MVAr using an impulse value of 25 kVArh. This telemeter also has the long-time-constant feature to eliminate pointer wobble on steady low-scale indications.

(*c*) Type 3.—66⅔ impulses/min with a response time of 30 sec for station total-generation, system-frequency, system-voltage and light-intensity indications. The 30 sec response time is necessary to accommodate irregular pulsing from generation summators. The normal stabilized supply to telemeters is 120 volts d.c., but by changing this to 95 or 150 volts and also changing the input capacitor, with the facilities provided any rate from 40 to 80 impulses/min can be accommodated to suit the station generation summator, provided that the rates from the individual generators to the summator are not less than 20 impulses/min for full generation.

(*d*) Type 4.—33⅓ impulses/min with a response time of 60 sec for station total-generation indication. By changing the stabilized supply voltage and the input capacitor this type will accommodate rates between 24 and 48 impulses/min provided that the individual generator full-load rates are not less than 12 impulses/min.

At the G.C.C.'s these telemeters energize 2½ mA (f.s.d.) indicating instruments and have adequate capacity for summation services. Types 3 and 4 are also used in power stations for local indication of total generation and are mounted in pairs, for active and reactive power, on a jack-in base complete with power pack. They are used with 5 mA indicating instruments and in some instances with indicators in boiler houses and engine rooms.

(6.5) Telemeter Initiating Devices

Contributing in no small measure to the success of the telemetering system, certain meter manufacturers developed three types of impulse meters to the requirements of the T.T.C. as follows:

(*a*) Meters which generated 66⅔ impulses/min for full-scale-deflection power indication (and 33⅓ impulses/min for reactive power) for feeder flow telemeters with both-way rotation and 3 transmitting contacts spaced at 180°, 270° and 360°.

(*b*) Meters which generated 66⅔ impulses/min for full-scale deflection at a rate proportional to the square of system voltage, using an induction meter with the current coils energized through resistors from a secondary winding on the voltage electromagnet.

(*c*) Meters for system-frequency telemeters with linear impulse generation between 66⅔ impulses/min at 45 c/s and zero rate at 53 c/s, using a double-element differential induction meter with discs tending to rotate in different directions, each under the influence of a separately excited series-resonant circuit.

A considerable saving was achieved by making use of impulses from station generation summators, but difficulties arose from the random arrival at the summator of individual generator impulses and the infrequent cancellation of generator impulses by 'house service' impulses of high impulse value. The Authority's meter engineers overcame these difficulties first by providing a time interval (0·7 sec) between successive impulses greater than the cyclic scan time of the 2-way coder-sender (see Section 6.3). Secondly, at stations where geared summators were employed the effect of the 'house service' impulses was reduced by decreasing their value and spreading the increased number more evenly. At stations where geared summators were not employed a regulator was provided which received the irregular pulses from the summator and mechanically averaged the rate by the storage of a few impulses before retransmission at a regular rate.

A daylight recorder had been in use in the London G.C.C. to assist in load dispatching. So that readings of daylight intensity could be telemetered over the standardized system, the Authority's research laboratories developed a light-controlled impulse generator.* This generated impulses ranging from zero to 60 impulses/min between darkness and light of 40 klx intensity and levelled off to 66⅔ impulses/min at 100 klx. The impulse generator, a blocking oscillator controlled by a light cell, is mains-energized and mounted on power station roofs. To check operation the light cell can be illuminated by a lamp inside the transmitter from a test switch inside the station.

(6.6) Telemeter Indications, Summation and Transmission to National Control

Telemeter indications are displayed on instruments with 270° scales as follows:

(*a*) 2½ mA (f.s.d.) for station generation, light intensity, system frequency and system voltage;

(*b*) 2½–0–2½ mA (f.s.d.) for feeder-flow active and reactive power;

(*c*) 0–5 mA (f.s.d.) at stations for station generation.

The feeder-flow instruments are arranged to have one or two Perspex-piped lights in the scale to indicate telemeter failure, feeder overload or active/reactive switching where single instruments serve 2 telemeters. The normal working portion of the square-law scales produced by the system-voltage transmitters [Section 6.5(*b*)] was too small and additional scale expansion was obtained by electrical zero suppression.

Fig. 8 shows the circuit employed for the indication of feeder flows and net area transfer. For total area generation and net

* HASLER, E. F., and SPURR, G.: British Patent No. 786196.

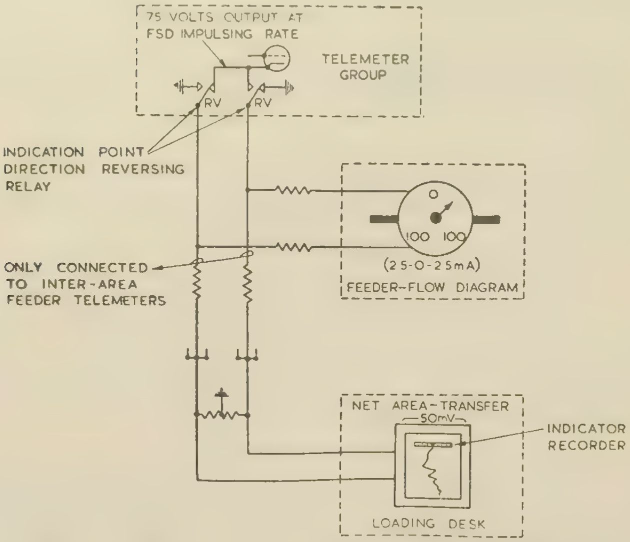


Fig. 8.—Feeder-flow and net area-transfer indication.

area transfer 10 in 50 mV slide-wire indicator-recorders of the chopping-amplifier type operate from shunts in the common return of summating resistors connected to the associated telemeters. Summation circuits with manual injection to preserve the total when telemeters are out of service, or small stations without telemeters are generating, are shown in Fig. 9.

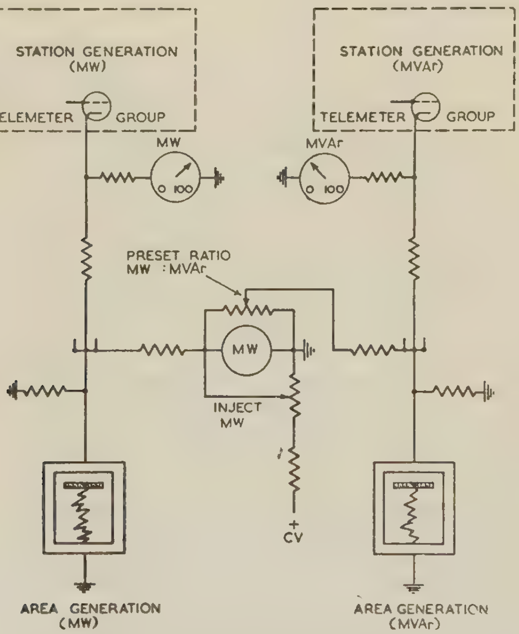


Fig. 9.—Summation circuits: area generation (MW and MVAr) with manual injection.

Transmission to National Control of total-area-generation indication is by means of an impulse generator controlled by a transmitting potentiometer in the loading-desk indicator-recorder. The action of the impulse generator is such that steady current applied by the potentiometer is balanced by a current obtained from an impulse frequency generated within the circuit.

(7) MISCELLANEOUS INSTRUMENTS

(7.1) Cyclometer Indicators

The control-room clock is impulsed by a 30 sec master clock which also impulses stepper switches and relays to produce a different switching pattern to correct the cyclometer indicators in the control-desk logging clocks every 60 sec. These indicators, and those used for area-generation instruction and at National Control for area-generation cost indications, have Perspex wheels turning freely in either direction and engraved with numerals or letters as required. Each wheel has a magnet which turns the wheel under the influence of a star-wound stator winding. Each of the three stator terminals can be open-circuited or connected to negative or positive direct current as required, to turn the wheel into any of 12 different positions.

Cyclometers indicating system time error are driven through a differential by two synchronous motors, one operating from the system and the other rotating in the opposite direction from a crystal-controlled 50 c/s supply.

(7.2) Rate of Change of System Frequency

Indication of rate of change of system frequency is obtained from a feedback amplifier arranged to differentiate changes in the d.c. output of a telemeter operated by a rotating frequency-impulse meter [Section 6.5(*c*)]. The indication is scaled $\pm 0\cdot 2$ c/s/min. To ensure that changes in the d.c. output are due only to variations of system frequency, a slow-response telemeter [Section 6.4(*d*)] energized from a stabilized supply is used with half-value impulses at double rate.

(7.3) System Frequency

System-frequency indication is obtained from the local 240-volt mains supply, but if this should fail the instruments are automatically, and at any time can be manually, switched to an amplified remote system-frequency signal. The signal is obtained from one Grid station in the area over a 2 580 c/s channel of 240 c/s bandwidth with Grid-frequency modulation. The system-frequency instruments are conventional continuous-balance 10 in indicator recorders (48·5–50·5 c/s) and 28 in circular-scale indicators (47–51 c/s), and are accurate to within 0·01 c/s down to 190 volts. They are independent of waveform; to achieve this they employ a synchronous switch which charges and discharges a capacitor. The resulting d.c. impulses are applied to an integrating network whose output is directly proportional to system frequency.

(7.4) Station Generation Instructors

On the loading desk are coded selection transmitters which the loading engineer can set to send total 'sent-out megawatts' generation instructions (see Section 3.2) to individual power stations. The settings are indicated by pointers which move round the scales of the station megawatt generation telemeters in 1% steps. The 100 steps are encoded in binary fashion by means of 7 cam-operated change-over contacts and a gear train arranged behind the megawatt telemeter. Together with the associated active and reactive power telemeters, 30 or more station instructors can be mounted within reach of the loading engineer.

At the power station the generation instruction selections are decoded and stored on 7 relays which switch binary graded resistors singly or in parallel in the separate coils of a ratiometer instruction indicator scaled in megawatts. The ratiometer instrument is energized from the 50-volt station battery and is independent of battery-voltage variation.

(8) POWER SUPPLIES

(8.1) Mains Supply and Standby Diesel-Driven Alternators at G.C.C.'s

Power for the control equipment and essential lighting at a G.C.C. is derived from the local mains supply and from a standby 12 kW single-phase 240-volt Diesel-driven alternator, pushbutton controlled from the control and apparatus rooms. Fifty-volt d.c. lighting comes on automatically during supply failure. The 12 kW 2-cylinder enginer set is inside a protected building, and cooling is by a sealed system of external air circulated by the radiator fan. An immersion heater in the cooling system prevents freezing and ensures reliable starting. For the domestic needs of the control establishment an automatic-starting single- or 3-phase 25 kW Diesel-alternator with automatic load change-over is provided usually in the office block.

(8.2) 50-volt D.C. Supply at G.C.C.'s

The common 50-volt d.c. supply at the G.C.C. is from two 24-cell 100 Ah lead-acid sealed-top batteries in parallel and constant-voltage chargers with filters to reduce charger noise to 2 mV (C.C.I.F. weighting). The positive pole of the 50-volt supply is connected to the station earth system, of resistance less than 8 ohms under drought conditions, and separate from the earthing systems for the mains or Diesel power supplies.

(8.3) Power Supply for Electronic Equipment at G.C.C.'s

Valve-heater supplies at the G.C.C.'s are distributed to the jack-in groups from 50-volt rack transformers, which are fed from a 4 kW 240-volt regulated mains supply. During mains failure and until the standby Diesel is on load the line amplifiers and v.f. signalling equipment are maintained by the 50-volt battery supply.

Main and reserve banks, each consisting of three 250-volt smoothed d.c. power packs, are provided at the G.C.C. One 250-volt supply is for the 10-way decoders; the other two form a 500-volt supply with earthed centre-tap for the telemeters. Specially insulated jacks are provided on the racks to connect these supplies to the jack-in electronic equipment. Because of the general unreliability of low-current fusing, these 250-volt supplies are fed to the individual telemeter and decoder groups through metal-filament lamps, which glow in the event of a short-circuit within the group without appreciably affecting the supply to other groups.

Each telemeter rack has a jack-in power group energized at 50 volts from the regulated mains supply, to supply constant direct current at 95, 120 and 150 volts [see Section 6.4(*c*)] to the 48 telemeter groups mounted on the rack.

(8.4) 50-volt D.C. Supply at Outstations

At outstations the d.c. supply to the standardized system is obtained from a 50-volt d.c. distribution board which also supplies other station services. The board is energized from a 24-cell lead-acid battery maintained at 52·8 volts by a constant-voltage charger filtered to reduce hum to 2 mV (C.C.I.F. weighting). 'Charger fail' alarm is signalled by a moving-coil relay at 50 volts. The on-site test limits for the standardized system are 46 and 54 volts.

(8.5) Telemetering Supplies at Outstations

Although 50-volt station batteries are adequate for general services and signalling, thermionic valves requiring 250-volt supplies had to be used in the multiplex telemetering system; it might have been otherwise had transistors of proved quality been available in 1950. The use of h.t. batteries or battery-driven alternators was rejected in view of the additional cost and maintenance charges at about 200 stations, and the fact that there is usually nothing to telemeter when the mains have failed. It was therefore decided to make use of the most secure 240-volt mains supplies available at the stations and to make sure the telemetering system would operate down to 190 volts and be independent of variations of system frequency. The supply is transformed to a constant 50 volts and fed through the shelf-jack contacts of the coder-senders to energize power packs for h.t. supplies and to heat the valves. The constant-voltage supply was a precaution to ensure satisfactory valve life.

(9) MISCELLANEOUS

(9.1) Test Facilities

In the G.C.C. apparatus room a desk with test junctions to jacks on the apparatus racks, where adequate test cords are provided, affords comprehensive facilities for the testing of rented circuits, line signals, signalling equipment, telemeters, indicating instruments, and speech levels. A standard cell and potentiometer device is provided to adjust master reference supplies of 95, 120 and 150 volts for the calibration of telemeter power groups (Section 8.3). A variable-rate impulse generator controlled by a clock movement provides a variety of impulse rates for injection into any telemeter. A loudspeaker and amplifier on the test desk can be used for monitoring lines, and, by heterodyning against a local reference oscillator, can be used to check the precise frequency of out-station oscillators.

The jack-in v.f. equipment has built-in test facilities for transmission and setting-up measurements. At the outstations, the multivibrators on the 10-way coder-senders are adjusted to mains frequency when it is known that the system is precisely at 50 c/s. For testing purposes the coder-senders can be switched so that no meter mark signals are transmitted but only the scan start and stop signals.

(9.2) G.C.C. Alarms

The provision of an alarm system for the G.C.C. control rooms was resolved only after a number of proposals had been investigated. In the system adopted a two-tone chime is operated once on every circuit-breaker and current overload operation. The principle of an audible alarm sounding continuously until the last indication had received attention was not acceptable. Similarly a short buzz signal is sounded on all calls from outstations and for miscellaneous alarms.

When an alarm is sounded, the appropriate panel on a large stencil indicator in the control room flashes or lights steadily as required. Either or both of the audible alarms can be regenerated every 10 or 30 sec or dispensed with altogether if desired, as they are additional to the supervisory signals on the individual station equipments.

(9.3) Equipment in General

Equipment in the G.C.C. apparatus rooms is mounted on open telephone-exchange-type racks, the rooms being kept at normal temperatures and constructed so that dust is unlikely to be created. In the localities concerned air filtering is not necessary.

In the past it was general practice to mount equipment associated with a station on a single rack or section of rack, and to allocate space for its future requirements. This wasted valuable accommodation space for stations which did not expand, and necessitated providing additional mounting space elsewhere for stations which outgrew the original allocation. This experience has led to the racks being arranged on a functional basis (line racks, telemeter racks, amplifier racks, etc.), and, in general, they

are wired to a distribution frame, where the various units are connected to form a complete station equipment. The distribution frame is also used to terminate the connections from the control room, which is cabled for ultimate capacity. This minimizes the work to be done in the control room as the system grows.

At the outstations, apparatus is jacked into racks contained in dust-proof cubicles. Two cubicle arrangements were adopted, one for minor stations and a larger one for major stations. The latter, however, could be arranged to cater for only the facilities required at the average station and it was necessary to provide overflow cubicles at major stations to cater for excess requirements, dependent minor stations and dependent satellite stations.

While the design of the furnishings of the control rooms is different in each control area, they conform to a standard pattern and are equipped with a loading desk, feeder-flow diagram, switching desk, switching diagram, clerk's desk, cordless board and a miscellaneous instrument suite. A full description of these is given in the companion paper.[6]

(10) CONCLUSION

Although a number of design features have had to be omitted from the paper, such as the planning parameters of the system and the development of equipment for the National control network, it is thought that sufficient has been explained to demonstrate the main design features of the country-wide and standardized system of communication, indication and telemetering now used to control the British Grid.

(11) ACKNOWLEDGMENTS

The authors wish to thank the Central Electricity Generating Board and the managements of the Automatic Telephone and Electric Company, the General Electric Company and Standard Telephones and Cables Limited for permission to present the paper. They take this opportunity to express their indebtedness to their colleagues and former colleagues on the Technical Committee, and in particular to the late Mr. R. H. Dunn who contributed so much to the design of the standardized system.

(12) BIBLIOGRAPHY

(1) Burns, G. A., and Rayner, T. R.: 'Remote Control of Power Networks', *Journal I.E.E.*, 1936, **79**, p. 95.
(2) Peattie, J. D.: 'Control Rooms and Control Equipment of the Grid System', *ibid.*, 1937, **81**, p. 607.
(3) Cooper, A. R.: 'Load Dispatching and the Reasons for it, with Special Reference to the British Grid System', *ibid.*, 1948, **95**, Part II, p. 713.
(4) Dunn, R. H., and Chambers, C. H.: 'Telemetering for System Operation', *Proceedings I.E.E.*, Paper No. 1400 M, October, 1952 (**100**, Part I, p. 39).
(5) Casson, W., and Gunning, P. F.: 'Methods and Channels for Control and Intertripping used on the British Grid System', C.I.G.R.É., Paris, 1956, Paper No. 307.
(6) Gunning, P. F.: 'Standardization of Control Facilities for the British Grid: Communications, Indications and Telemetering' (see page 554).

DISCUSSION ON THE ABOVE TWO PAPERS BEFORE THE SUPPLY SECTION, 28TH MAY, 1958

Mr. J. D. Peattie: An outstanding feature of electricity supply, and indeed of electrical manufacture for power purposes, is that the output doubles roughly every ten years. If the industry were static, supply engineers and manufacturers would still be faced with the problem of improving efficiency, but, in addition, they have to meet this doubling process every decade. In some ways it eases the problem, but in others it makes it more difficult.

During the years since the war there has been a tremendous upsurge of interest in control mechanisms of all kinds. Biologists are at work on the secrets of the control of life itself. Other people are controlling the great masses of men and women. On the material side there is a completely new section of activities in The Institution, dealing with control matters, where electrical engineers are producing instruments which assist and simulate the human brain in its work. Biologists compare its operation with that of a tremendous control room equipped with 15 million odd units.

Many engineering developments are very spectacular and have attracted much public attention. They lend themselves to propaganda. Others involve equally hard work and are equally important but less spectacular. The papers describe one of the latter type in the evolution of the control system for the British Grid to its present position. I think that is an outstanding example of what can be done by co-operation. It has involved three groups of engineers, the closely linked supply undertaking, the Post Office which supplies the communication system, and a group of interested manufacturers.

Nobody imagines, least of all the authors, that this is the final solution. Problems change, and operating engineers are notorious among their design and construction colleagues for changing their requirements as the problems change. The process will, no doubt, continue.

There are two matters to which I should like to refer. One arises from the very interesting diagram of the evolution of the communication system. My mind goes back to the analogy which was sometimes drawn between the Grid system of power circuits and a feature of the old struggle between the gladiators in Rome. One gladiator had a sword and the other a net. Contrary to what some people would think, the man with the best chance was the one with the net. It will be very difficult for any outside agency, enemy or otherwise, to break down the networks now developed round the control centres.

The second point to which I should like to refer is only mentioned very briefly by Mr. Gunning towards the end of his paper, namely the question of automatic load and frequency control. He indicates that a good deal of thought has been given to it, but is very discreet about the plan and the results. It is perhaps interesting to compare conditions in Europe with what is happening in this country. There the engineers consider that, in order to control the load transfers between countries and regions with the precision they require, they must run the networks in parallel and adopt automatic control of frequency and of load transfers. On the Continent the conditions are not so easy as in this country, where the whole of the electricity supply is under three undertakings. There is a large number of independent undertakings, and requirements for the load transfers differ widely. A 7-year plan, to standardize the arrangements for the load control and automatic frequency control, is now taking shape.

On the 18th December, 1957, at 5 o'clock, France, Belgium, Holland, Federal Germany, Switzerland, Austria and part of Italy were connected and running in parallel with a total load of about 35 GW, compared with our own figure at about the same time of something like 21–22 GW. Control centres for frequency and transfer control are being set up by the countries and supply undertakings. Measurements of transfers across the frontiers are brought back to these controls, which, in turn, send out control signals to their generating stations chosen for regulation.

Mr. Gunning has said very little about what we have in mind in this country. In this country we seem to have got on fairly well without automatic control, particularly in the immediate post-war period when frequencies fell to 48 c/s at peak load. However, when operating engineers decide that it is essential and persuade other people that it has to be provided, a scheme will soon be evolved and co-operative effort will again produce admirable plant like that described in the papers.

Mr. F. J. Lane: These two papers mark the establishment of a central control system, the magnitude and scope of which are unequalled anywhere else in the world. It was my privilege to support the authors in the preparation of their designs, estimates and programmes, and at times of difficult progress and finance. I can testify to their energy and co-operation and to the efforts of the works and Divisional staffs who have constructed and commissioned the equipment with quite remarkable freedom from 'teething' troubles.

The Grid Control Areas (see Fig. 2), which in C.E.B. days coincided with the administrative areas, have stood the test of time. The operational area is essentially determined by engineering considerations, and the pattern originally established has been largely self-preserving as the design of the system has developed to bring in the Supergrid.

The consistent use of Post Office channels is important. It has often been suggested that the supply organization is too dependent on another national undertaking and is unprogressive in making little use of private pilots, or power circuit carrier, or of radio, but, as Mr. Gunning indicates, any of these alternatives would have involved greater capital outlay, greater maintenance costs and, for carrier and radio, greater complexity of apparatus. The present arrangement gives a first-class technical and operational mechanism, which only needs a little more 'give-and-take' in special locations and emergency conditions to result in a perfect example of national planning.

One is struck by the way in which so much information is collected for the guidance of the Area Control Engineer and as a basis for loading allocations by National Control. The next step is surely for loads, circuit conditions and incremental costs to be fed into a computer, which, after making accurate adjustments for losses in the system, will automatically advise the Areas on the most economical load distribution and, later, may automatically allocate and control the generating-station outputs required.

Mr. A. J. Jackman: In the Post Office we are particularly pleased to have publicity given to this business of transmitting information and data over the telephone network because we hope to see it expanding in the future, with more systems of remote control and data transmission.

The bandwidth has been restricted to 2·4 kc/s because we started ten years ago; the system was to be very widespread and we could not always guarantee to give a wider band. It is a great pity because another 200 or 400 c/s in that bandwidth would improve the speech immensely, and we hope in the future to be able to give that at least. Also in the future we shall be spreading much more of our carrier system of working, and the facility for d.c. transmission will become less and less useful; thus we hope that an entirely a.c. system will be adopted.

A long private circuit must, in general, be built up from line plant of various types; it will begin and end on copper-wire pairs of small gauge in local line networks, and intermediately it will have pairs in junction or trunk cables which may or may not be loaded with inductances at regular spacing, and it may also use channels in one or more carrier systems. Naturally we make use of the flexibility thus made available to select a circuit suitable for the requirement. The transmission problems presented may differ from those of telephone speech.

We do not know all the answers concerning the various problems of data transmission, but as these systems evolve we hope we shall secure the co-operation of the designers and renters and have as interesting and fruitful a time as we have had with our colleagues of the C.E.A.

Mr. T. Sealy: With regard to the decision to use rented Post Office lines throughout the C.E.G.B. system, I consider that Mr. Gunning's argument has been biased in their favour. Their reliability is overstressed whilst that of power-line carrier is understressed, e.g. the effects of the East Coast floods on Post Office pilot circuits compared with the effects on power-line carrier circuits in the north of Scotland during the severe snowstorms when they were the sole physical network remaining in operation. The necessity for barrier equipment is used as an argument against aerial pilot cables but not against Post Office lines, which, more often than not, have similar requirements.

I suggest that the C.E.G.B. would have more confidence in its communication network if the main transmission circuits had been under their direct control. For instance, would it not be possible to use a power-line carrier system for the main trunk circuits, retaining Post Office pilot circuits for shorter circuits to attain this desirable state of affairs?

Standardization, which settles design policy on manufacturers, can be justified in this country at present only if the final product is also a marketable export, which this equipment is not.

The restricted speech range (400–2000 c/s) would not be acceptable to the majority of undertakings except on lines of minor importance. Improved speech range increases efficiency, so essential to modern control system operation.

To maintain the battery voltage at 52·8 volts, using a constant-voltage charger requires that periodic conditioning charges are necessary. If the equipment had been designed for a 48–56-volt range instead of 46–54 volts, the constant-voltage charger could be 'floated' across the battery at a voltage of 2·3 volts per cell, i.e. 24-cell battery equals 55·2 volts. This would, according to the battery manufacturers, eliminate conditioning charges.

Mr. P. W. Cash: Some of the new control facilities have been necessitated by important changes in the character of the Grid system. The first such change is the gradual transition of the 132 kV Grid from an interconnection system to a distribution system. Originally only a very small proportion of the output of the generating stations was transmitted over the Grid system. Now, the proportion is over 60%, with less than 40% going direct to the distribution systems, and I estimate that, by 1965, the proportions will be about 90% and 10%, respectively. The second change is the introduction of continuous parallel operation between Grid control areas, culminating in the Supergrid system. The third change is the intended transmission of appreciable blocks of power from one part of the country to another. These changes will entail much greater attention to reactive loading and voltage control, and the new indicating equipment provides for this.

The facilities for signalling incremental and decremental fuel cost quotations from Area Controls to National Control, mentioned in Section 5.6 of Mr. Gunning's paper, are needed for a new system of national load dispatching to be introduced shortly. At present, each Area Control regulates its generating station outputs so as to maintain, as nearly as possible, a constant net area import or export in accordance with an economic programme worked out by National Control, each programme lasting for 2–4 hours. Under the new system, inter-Area transfer instructions will be abandoned, except at times of rapidly changing load. Instead, National Control, constantly aware, from the new signals, of the Area in which the next increment or decrement of generation can be handled most advantageously, will give minute-to-minute instructions of total generation required from each Area, in the same way as Area

Controls instruct total generation from each power station. Already, with the Supergrid system only half-completed, the fuel savings attributable to parallel operation of the Grid areas have reached a level of about £3 million per annum; improvement in the efficiency of inter-Area load dispatch thus offers a useful return.

Mr. T. B. D. Terroni: It seems rather strange, in reviewing the progress made during the last 25 years since I was engaged on work of this nature, to find that the system which had been standardized for communication was one based on a line which could not transmit a frequency higher than 2·4 kc/s. Having catered for two telegraph channels above 2 kc/s and a signalling channel below 400 c/s, the effective bandwidth remaining for speech was cut to 1·6 kc/s, a bandwidth considerably narrower than that provided for normal good-quality Post Office circuits which transmit a band of 300–3 400 c/s.

It might be argued that intelligibility is not severely impaired by reducing the bandwidth, for the simple reason that the maximum energy is contained in the band 400–2 000 c/s. It must be realized, however, that the criterion of a telephone circuit cannot be judged by intelligibility alone, for if this were so it could be provided with a bandwidth of 300 c/s by using a voice coder, but it would be the intelligibility of a community of frogs croaking at each other.

The control engineer carries out practically the whole of his daily business over the telephone, talking to the substation attendant or to a power-station engineer, or to divisional headquarters if not National Control. It seems essential that he should be provided with adequate means for establishing human relations with his colleagues, and this can be achieved only with a good-quality circuit, which would have the added advantage of reducing mental strain and leaving the control engineer psychologically free to face any emergency which might arise, for instance, when the Grid system is tripped on a fault.

The designers have evidently been compelled to accept a relatively poor circuit performance guarantee, and the reason that a 1·6 kc/s bandwidth has been accepted as 'not too bad after all' is that they have been aided and abetted in their judgment by the shortcomings of the telephone instrument. Perhaps future demands for more telegraph circuits to provide statistical information for National Control will use up this 1·6 kc/s bandwidth and warrant an entirely separate good-quality telephone circuit for the control engineer.

Mr. W. Casson: When it was decided to modernize the control centres it was realized that it would be a big job; but it was made much simpler by the decision to provide new control centres, so that, when these were equipped and tested, the change-over could be carried out in a single operation, which was much better than the alternative of modernizing the old control centres in the same buildings. The design of the whole equipment to be provided in the new centres was entrusted to Mr. Gunning and the T.T.C. in close liaison with the system operation branch. Steps were taken to ensure that the views of those who would use the facilities and maintain the equipment were taken into consideration at a very early stage.

It is regrettable that transistors have not been used in place of thermionic valves in the equipment, but as stated in Section 8.5 of the paper by Messrs. Burns *et al.*, when the designs of the equipment had to be finalized transistors were not proven and the risk could not be taken. I have no doubt that, if it is found economic, we shall have transistorized equipment in due course.

Mr. Gunning's paper shows the way in which two useful additions to the main scheme of control equipment have been made—inter-tripping and limited selective control. The latter term implies some restriction in what the equipment will do: the limitation concerns the number of indications which can be carried out on a standard equipment. This form of control is the only one of this type which can be carried out over long distances. To be wholly effective it is essential that it should be used with tele-auto-reclosure equipment. These forms of control have been most successful up to date and make a big contribution to the efficient use of manpower and the security of the equipment. I think that, as time goes on, we must use more automatic control of stations.

Mr. H. F. R. Taylor: Owing to the delays in the commissioning of the standardized equipment, for which there are good and sufficient reasons, the operating staff found it very embarrassing to have to make use of non-standardized equipment to get intelligence from one part of the country to another for the purpose of national control. For that reason alone a standardized system is essential in this country, whereby we can, at will, interchange telemeter readings between Areas and National Control and between one Area and another. Without a standardized system stations could not be changed from one Grid control Area to another as the network develops, making it more convenient that a station once controlled from one Grid Control Centre should be transferred to another Control Centre.

I should like to make a strong plea for the retention of this standardized system throughout the whole of its life. We do not want stagnation, and provisions have been made for the improvement and development of the standardized system, but that does, to some extent, curb the enthusiasm of the people it is so necessary for us to have, who look forward and try to improve anything they have got. They must be a little patient while their proposals are examined before adoption as a modification of the standardized system. Thus we shall avoid the development of separate standardized systems in different parts of the country of which may be, to some extent, incompatible.

As well as the co-operation on the technical side through the design and construction of the standardized system for the Grid Control Centres there was very close co-operation with the operating personnel. We knew the limitations of the previous control equipment and were confident we could make improvements.

Many of us had experienced some degree of strain in the control rooms, eyestrain in particular, owing to the continual changing of focus of the eyes, often to read meters which had never been designed from the point of view of the user. We therefore made many attempts to rationalize the control centres, although not to standardize them, so as to give maximum utilization with the minimum of effort, bearing in mind that between 2 and 4 a.m. one is not as alert as at other times of the day and wants facilities so provided that they can be operated and seen with a minimum of effort. We therefore designed meters specially for that purpose.

We had regard to a paper by Mr. Golds* and designed meter scales based on his suggestions, using square instead of round character numerals on the 4 in feeder-flow meters.

We adopted two scale markings—a large one, $\frac{1}{4}$ in × $\frac{3}{64}$ in thick and a short one, $\frac{1}{8}$ in × $\frac{1}{32}$ in thick and used a 1·6 : 1, height/width ratio for the numerals. No maker's name or the like appears on the face of the meter and the zero adjuster is centralized in the black centre piece and therefore not noticeable. We used the black dot in the centre so that the eye can easily pick it up and then look along the pointer with comparative ease, rather than trying to pick up a black pointer in the middle of a sea of white. Platform scales were adopted to reduce shadow and anti-reflecting glass to cut down glare, and we are very satisfied with the results.

* Golds, L. B. S.: 'A Survey of Modern Methods of Presentation of Instrument Readings and Recordings', *Proceedings I.E.E.*, Paper No. 1152 M, May, 1951 (98 Part II, p. 671).

Mr. N. A. F. Williams: I have noted particularly the remarks in the paper by Messrs. Burns *et al.* to the effect that the difficulty in having to provide 250-volt h.t. supplies for valves might not have arisen had transistors been sufficiently reliable in 1950. I feel that transistors and semi-conductor diodes will be employed in future equipment, particularly to replace relays and other electro-mechanical devices which might be used in the coding of transmitted impulses or in the decoding of received impulses in multiplex-type systems.

This should result in greatly increased sending speeds, and as an example of this I should like to describe some aspects of an equipment developed by the company with which I am associated. This equipment does, in fact, employ transistors and semi-conductor diodes and provides two-way transmission of up to 200 on–off signals in each direction, each signal being derived from a pair of contacts and ultimately operating the appropriate relay at the far end. The transmission time between the closing of any pair and the operation of the appropriate relay is about one second or less, regardless of what other codes may be transmitted at the same time. The received signals are, in fact, integrated so that the relays cannot be operated by spurious electrical interference. We have constructed a small prototype equipment based on the plug-in unit type of construction.

Mr. B. Webb-Ware: There is one striking difference between the equipment described in the papers and the original Grid equipment. Now it enjoys full accommodation facilities, whereas the other equipment had to be hidden in some odd corner, but there are one or two things which are familiar. Speech seems to be very much the same as it was 20 years ago, and are the megavar scales really determined by operational requirements? Is a transfer of 300 MVAr on a 275 kV line envisaged, or are the scales more related to the characteristics of the current transformers and originating instruments to avoid current-transformer saturation?

The reference to transistors in Section 8.5 of the paper by Messrs. Burns *et al.* does seem to show the pitfalls of full standardization. After all, the decision not to employ transistors was taken in 1950, eight years ago. There are many merits in standardization, but I hope that some of those who have contrived the new standardized system as the fruits of enthusiastically de-standardizing the system which has gone before will leave room for those who come after to do the same thing.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSION

Messrs. P. F. Gunning, G. A. Burns, F. Fletcher and C. H. Chambers (*in reply*): A popular charge against standardization is that it impedes progress and is a brake on the adoption of new ideas. This might be true for new and rewarding fields of engineering, but in the long-established field of line signalling it is more likely to be a convenient cover for complacency. Even if the charge had some validity it could not be sustained against the 'standardized system' because the design is at no time complete. Development is still going on; it started 10 years ago and will continue for as long as the agreement lasts between the C.E.G.B. and the manufacturers. Only the constituent items of the system have been rigorously standardized, so that they may be used in different combinations at different stations. There is no doubt that a number of these standardized items will be replaced by improved versions as worth-while improvements become available, such as transistorized versions of the voice-frequency thermionic equipment.

We do not share the novel view advanced by Mr. Sealy that Great Britain, which has the largest unified power system in the world, should be denied the benefits of standardization merely because undertakings in other countries are still in the experimental stage.

Mr. Peattie refers to changing requirements. Already we are having to develop a larger 'limited selective control' system, and, because of the railway electrification programme, to make provision for automatic communication with the railway electrical control centres at out-stations on the Grid control networks. In view of changing conditions the security of the control networks has recently been reassessed, and they are to be reinforced by alternative means of communication.

Mr. Peattie also refers to the use of automatic frequency and transfer control which has now become a necessity in Europe with the interconnection of a number of national power systems. With most of Britain's generating plant under unified control and with no a.c. transmission system to the Continent, there is not the same need for automatic control in this country. However, in the system under consideration, uneconomic generation resulting from automatic frequency control would be minimized by spreading the control over the country's spinning reserve. Since the majority of the generators running at midday in this country are shut down at night, it would be necessary to equip most of them with automatic load controllers, so that, at times when they are contributing to the country's spinning reserve, they would respond to the control level broadcast from the control centres and so participate in the overall frequency control.

Mr. Lane refers to the ultimate use of computers to allocate and control the generating-station outputs. Whether or not the overall cost of computer control for the large C.E.G.B. control areas could be justified is a matter for operating engineers and computer manufacturers, but interconnection between the 'standardized system' and the computer should present no real technical difficulties. Selective control from the control centres of the individual load controllers would be provided over the same channels which would be used for the high-speed automatic control of the spinning reserve.

Various speakers refer to speech quality, and advance the view that speech restricted to 2 kc/s imposes a serious operational limitation. We would agree with this view if the speech-transmission level had remained as poor as that with the old control networks. With the transmission levels now generally available and with fully-equalized 4-wire transmission, the restriction is not perceptibly inferior to the shortcomings of the telephone instrument referred to by Mr. Terroni. When, in due course, the wider frequency band referred to by Mr. Jackman becomes generally available, we would change to a higher speech cut-off frequency, but only if it proved worth while and we were sure that the operating engineers would not require the extra bandwidth for yet more facilities.

It is to be expected that the performance of power-line carrier in the sparsely populated Highlands of Scotland would be superior to that which would have been obtained with rented telephone circuits in the same area. However, in the C.E.G.B. territory, with more than 300 Grid transmission stations and the number steadily increasing, long transmission lines are a rarity and soon become split up with the addition of new stations; it is just not possible to set up a main trunk system in England and Wales based on power-line carrier. The record of 25 years' satisfactory experience with Post Office circuits confirms the complete confidence of the C.E.G.B. in the continued use of rented circuits. It is of interest to point out that, in France, a country noted for its intensive use of power-line carrier, long-distance rented networks are now being used for the national control of the power system.

Mr. Sealy suggests that the 50-volt telephone-type equipment should be designed for 48–56-volt operation with the battery continuously charged at 55·2 volts. Under mains-failure conditions the voltage of the 24-cell lead-acid batteries falls to 48 volts almost at once, and there would then be no operating margin in the equipment and no allowance for voltage drop in the d.c. distribution. Most of the apparatus, the relays and the uniselectors, are designed to Post Office standard specifications, with limits of 46–52 volts. It was only after consulting a leading battery manufacturer and the Post Office in 1948 that we decided on the range 46–54 volts, with the battery normally operating at 52·8 volts (i.e. 2·2 volts per cell) to ensure that it would substantially regain its capacity after shut-down periods. Since then we have had no occasion to change the decision.

Mr. Williams forecasts that semiconductor devices and transistors will in time replace relays and electromagnetic devices in the multiplex equipment and thereby enable higher operating speeds to be obtained. In the 10-way multiplex equipment there are neither relays nor electromagnetic devices other than those connecting with external equipment—the initiating impulse meters, the telemeters and the voice-frequency receiver. We agree that the thermionic equipment might, in time, be replaced by transistorized versions, but we cannot achieve any greater sending speeds than those already imposed by the 50-baud limitation of the 120 c/s-bandwidth signalling channels. Speed of signalling has never presented a problem, since the telemeter response times are determined solely by the impulse rates available from the power meters, and not by the 50-baud limitation on the signalling channel. In the system referred to by Mr. Williams with 400-baud transmission (i.e. 200 signals in each direction within a second) the signalling channel would require a bandwidth of nearly 1 kc/s.

The suggestion that MVAr scales are determined by technical difficulties is incorrect. Already in one area the operation engineers are considering increasing reactive scale values to be the same as for active power. The technical difficulties referred to by Mr. Webb-Ware do not exist with pulse-modulated telemetering, which is adaptable to any scaling requirement.

DISCUSSION ON

'SUPPLY-VOLTAGE AND CURRENT VARIATIONS PRODUCED BY A 60-TON 3-PHASE ELECTRIC ARC FURNACE'*

NORTH-WESTERN CENTRE, AT MANCHESTER, 6TH MAY, 1958

Mr. H. Anderson: I am doubtful whether the cyclic variations in voltage and the transient effects described by the authors are the cause of the flicker noticeable in lighting. Generally, the thermal capacity of filaments and the afterglow of fluorescent tubes will obliterate these variations. Of much greater importance, in my view, are the current variations of the type shown in Fig. 6, where variations of 300–500 amp at 11 kV are taking place every six seconds.

Some further tests have been taken at the 66 kV busbars of the primary substation which now supplies this furnace and which is the point of common coupling with other consumers. The fault level at this point is of the order of 900 MVA, and yet with current swings of 75 amp at 66 kV, the voltage variation recorded on a special instrument did not exceed 0·5%. The power factor of the load swing is obviously important in predicting correction plant capacity to limit voltage variation. In our attempt to estimate this, a large number of current and corresponding voltage variations in the chart records were used to calculate the system impedance, and from this to work back from the known system impedance at the test point to the power factor. The value obtained using this method was 0·45.

Caution should be exercised in the use of standard recording voltmeters on systems where rapid voltage variations are taking place. The extent of the variation, or in some cases its existence, is not revealed by such instruments, and furthermore no two instruments give similar records under identical conditions.

Mr. K. W. Cartwright: The effects on the supply system of connected equipment represent a problem which is causing embarrassment both to the supply industry and the many industrial users of heavy electrical plant, particularly large rectifier-fed reversing drives, which are being considered by the steel and coal industry. When considering the cost of these installations the cost of the connections to the supply network should be included.

Mr. G. C. Wilson: My remarks on the question of arc furnaces on a public supply system are mostly related to practical experience on the Manchester supply system.

A large steel works operating in the Openshaw area of Manchester has installed three 30-ton and one 10-ton arc furnaces connected to an internal 6·6 kV system. This system is supplied through two 25 MVA transformers from the 33 kV system directly connected to a generating station.

Voltage fluctuations, amounting to 3% on the main 33 kV system, occur during the melting periods. This is reflected from the busbars of the generating station to wide areas of north-east Manchester. These voltage disturbances have been for many years the source of complaints from individual consumers. The matter is accentuated to some extent owing to the fact that, during the evenings, generating plant on the busbars may be at a minimum, and the consumers are more aware of the disturbance as they are using electric lights and television sets.

In the near future, an additional 30-ton arc furnace is being connected directly to the 33 kV system, and further trouble is envisaged.

One outstanding difficulty which is likely to occur on the supply to large arc furnaces is that, if a separate Grid connection is made through a 45 MVA or even a 60 MVA step-down transformer, the fault level on the 33 or 11 kV system is likely to be quite low, in the neighbourhood of 300–400 MVA, and the disturbance on this local system may be severe. Unless the rest of the steelworks, i.e. laboratories, administration offices, main works, rolling-mills, etc., is supplied on the normal distribution system not related to the Grid supply, severe disturbance will occur within the works themselves.

The overall costs of the provision of special 132 kV supplies to steelworks can be very heavy indeed, and it may be questionable

* Robinson, B. C., and Winder, A. I.: Paper No. 2456 U, December, 1957 (see 105 A, p. 305).

from a national point of view whether the increased use of arc melting furnaces is really a worth-while proposition.

Dr. B. C. Robinson and **Mr. A. I. Winder** (*in reply*): Mr. Anderson suggests that the current variations causing flicker might take place at about 10 times per minute. Our recollections are that they are much more rapid than this, which would be seen as a variation rather than a flicker. The variations of current shown in Fig. 6 are probably distorted owing to the limited response of the recording ammeter, as commented on by Mr. Anderson. The current variations on the oscillograms (Figs. 3 and 5) are more likely to be accurate with respect to frequency, though they are uncalibrated for amplitude.

Two factors appear to influence the way in which lamps show flicker. In the heated-filament lamp the heat capacity of the filament will tend to obliterate the current variations, but this is not adequate at the flicker frequencies. In discharge lamps the light output is less affected by voltage than in filament lamps. Test flicker circuits built since the discussion indicate that filament lamps, despite their greater heat capacity, show the flicker more clearly.

The fact that the power factor is about 0·45 indicates that it is lower than was given in the London discussion, and it would appear that an improvement in this would reduce the amount of flicker obtained.

DISCUSSION ON 'DEVELOPMENT OF TRANSPORTABLE THERMAL-STORAGE SPACE HEATERS'*

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 18TH FEBRUARY, 1958

Mr. C. R. Taylor: Thermal-storage heaters are by no means new, but they have attracted general interest only during the last decade or so. The present widespread interest shown in them must be a source of some gratification to the author, as it follows the pioneer work he has done to overcome the limitations from which earlier models and installations suffered.

The development of night-time loads is of increasing importance in view of the higher cost of post-war generating plants and distribution systems. The large generating sets and the nuclear stations now under construction and proposed will not be easy to shut down and re-start, and their low cost of generation will, to some extent, depend on their being continuously loaded to capacity.

While appreciating the need for careful investigation of new installations and the importance of avoiding mistakes, we should not be excessively cautious. The relatively stable cost of electricity, in the face of increasingly costly alternative fuels, makes electric heating progressively more competitive in the heating field. We can now in certain cases compete even with central heating. It is not unknown for the use of electrical heating to be discouraged for some perfectly sound technical reason, and for it to be found later that the rival system, when installed, suffered from even more serious shortcomings. The difficulties which face alternative fuels should never be underrated or ignored. In particular, flimsy structures are difficult to heat by any system, but, in some instances, the problem is not to maintain a steady temperature, but to keep the contents dry and in good condition. Thermal-storage heating may do this very well.

Would the author agree that thermal storage has a future in the domestic field, and if so, would he say what steps can be taken to extend the use of this type of heater to the home without attracting a penal burden of purchase tax? Why should change of state not be employed in thermal-storage heating? It would appear very attractive to have a relatively large amount of heat released at a selected temperature.

Mr. A. J. Francis: There is no doubt that the development of the transportable thermal-storage space heater is a valuable asset to the heating engineer, giving him a method of heating in which the running costs are competitive with other forms of heating, and, from the supply-undertaking point of view, it is valuable in improving the system load factor.

* BATES, E.: Paper No. 2284 U, February, 1957 (see **104** A, p. 415).

The main difficulty in applying this type of heater is with small installations of one or two heaters, where the method of control is often only a time switch. In such cases, the reputation of the heater has probably suffered from wrong use, and the only complaints I have heard have been concerned with this.

We ought to concentrate some thought on producing a heater which would be fully automatic, in which the charge would be cut off when the temperature of the block had reached a predetermined maximum and the heat radiated from the block could be adjusted to suit the requirements during the day.

Mr. E. Bates (*in reply*): The problem of maintaining sufficient night load on nuclear stations and large generators, however driven, in order to secure continuous running at high thermal efficiency is a real one, and the extended use of electricity for thermal-storage heating might well help in its mitigation.

The present position of purchase tax effectively precludes the use of night storage heaters for domestic purposes, but it is considered that a future lies in this direction. It might well be that, because of the normal requirements for domestic heating (where rooms are often not occupied until relatively late in the day) modified designs of heaters will be necessary, but it is known that already investigations are being made into methods of delaying the emission of heat by means which can be controlled by the user.

It is obviously attractive to use as a storage medium material of such a nature that advantage can be taken of its change of state. Unfortunately, the majority of these materials have other disadvantages not readily surmountable, but here again investigation is proceeding.

It is felt to be imperative for satisfactory operation that all installations of block storage heaters should embody thermostatic control, otherwise comfort conditions are not maintained and a wasteful use of energy usually results. The extent to which automatic control can be applied is mainly dictated by economic conditions, so that, for the small installation to which Mr. Francis refers, the use of simple room thermostats is usually all that can be justified.

It is suggested that there would be no particular advantage in controlling a heater by the temperature of the storage medium. In fact, if such a controller were to disregard ambient temperature, it would be ineffective as a means of maintaining comfort conditions.

621.315.051 : 621.311.21

The Institution of Electrical Engineers
Paper No. 2583 S
Mar. 1958
©

THE DESIGN OF THE 330 kV TRANSMISSION SYSTEM FOR RHODESIA

By F. C. WINFIELD, M.Eng., M.I.E.E., Fellow, American I.E.E., T. W. WILCOX, M.I.E.E., Member, American I.E.E., and G. LYON, M.Sc.(Eng.), M.I.E.E., Member, American I.E.E.

(*The paper was first received* 18*th November*, 1957, *and in revised form* 18*th January*, 1958. *It was published in March*, 1958, *and was read before the* NORTH-EASTERN CENTRE 24*th March*, *and the* SUPPLY SECTION 30*th April*, 1958.)

SUMMARY

The Kariba Gorge hydro-electric scheme now under construction by the Federal Power Board of Rhodesia and Nyasaland will provide the power for a major increase in electrification in the Federation. Outputs of 1 200 MW and 8 000 GWh per annum or more can be generated, and a 330 kV system is being built to transmit the power to the consuming centres over distances of above 300 miles. The paper outlines the conditions governing the design of the system, describes the steps taken to select the system voltage and other main features, and discusses some of the factors affecting the characteristics and design of the equipment.

(1) INTRODUCTION

Northern and Southern Rhodesia are separated by the Zambesi, which is one of the principal rivers of the world and offers prospects of hydro-electric development. The development of both territories is proceeding rapidly,[1] but it is only now reaching the stage at which power is needed on the large scale necessary for the economic use of the Zambesi and its main tributaries.

In Nyasaland development so far is on a smaller scale and in regions so distant from the area to be served from Kariba that interconnection is not foreseen in the immediate future. Consequently the paper is confined to consideration of transmission in Northern and Southern Rhodesia.

A map of Rhodesia is given in Fig. 1. With few exceptions, the principal towns lie in the copper belt of the Northern territory and in the midlands zone of the Southern territory. Large tracts in both territories are sparsely populated and virtually undeveloped. The average altitude is over 3 000 ft and the more populated regions rise to about 5 000 ft. Some parts of Rhodesia are very fertile, but much of the territory is rolling country covered with small trees in which conditions are primarily controlled by the seasonal rains.

The industries are mainly agricultural and mineral. There are large deposits of copper in the north and of coal in the south-west. Many other minerals exist and some are extracted in considerable quantities. The export of raw ores is giving place increasingly to the production of refined materials.

The indigenous energy resources of Rhodesia are in the extensive coalfield around Wankie and smaller, mainly undeveloped, fields elsewhere, and the hydro-electric potential of the rivers. Both are remote from the main consuming centres. Coal is used for the generation of electricity in all the larger existing power stations, but limitations of transport have led to some wood firing of power stations in the copper belt.

In the Federation, where power and transport are the two main factors limiting development, hydro-electric power has considerable advantages over thermal power, and this has led to the exploration of likely sites for hydro-electric development.

Detailed surveys of the Zambesi near Kariba Gorge, and of its tributary the Kafue, which joins it near Kariba, were made before federation by agencies of the territorial Governments, assisted by panels of technical advisers. The power potential, economics and constructional aspects of developing the gorges were the subjects of several reports.[2-5] These reports also examined the cost of extended thermal generation compared with that of hydro-electric power including transmission, and concluded that the latter would be cheaper.

The adoption of the Kariba scheme was announced by the Federal Prime Minister in March, 1955. The Federal Hydro-Electric Board was reconstituted in May of that year and was charged with the duty of building the Kariba scheme together with the associated transmission system. In May, 1956, the Federal Power Board (F.P.B.) was established under the Electricity Act, and superseded the Hydro-Electric Board.

The preliminary stages of the Kariba project had occupied several years, during which the actual demands and estimated future requirements for electricity had increased substantially. Similarly the estimated power potential of the selected site increased as more exact surveys were made. Consequently it was necessary to make changes in the schemes proposed in the earlier reports. Immediately before specifications for the plant were issued the transmission requirements were reconsidered in the light of the latest estimates of load and generating capacity. The paper describes the design of the transmission system now under construction. Some of the civil engineering aspects of the project have been described elsewhere.[6]

(2) GOVERNING CONDITIONS

(2.1) Power Demands

The demand for power has been rising rapidly in Rhodesia; for example, the average annual rate of growth in Salisbury in the ten years 1945–55 was 16%. Rates of growth such as this are so high that it was thought prudent to use lower rates for estimating the demand in the later stages of the project. In view of their importance, the load estimates have been carefully reviewed and checked, and experience has since indicated that they were, in fact, conservative.

Table 1 shows the estimated load development in the various

Table 1

ESTIMATED LOADS (DECEMBER, 1955)

Year	Rhodesia Congo Border Power Corporation and Ndola Corporation	Salisbury Corporation	Southern Rhodesia Electricity Supply Commission	Bulawayo Corporation	Total load without diversity
	MW	MW	MW	MW	MW
1960	242	112	188	82	624
1966	340	191	363	134	1 028
1971	445	273	562	187	1 467

The authors are with Merz and McLellan.

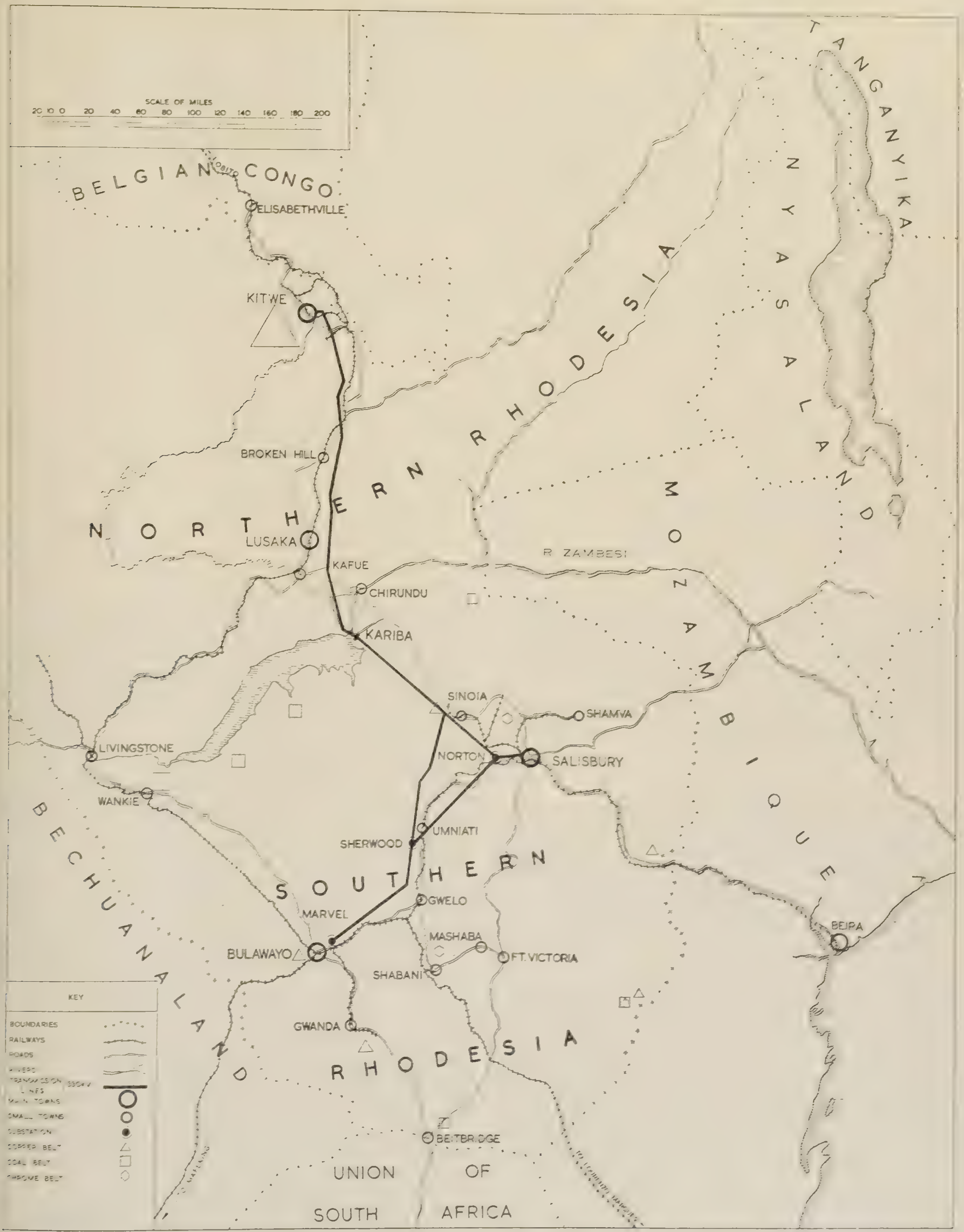


Fig. 1.—Map showing location of transmission scheme.

centres, which is a governing factor in the construction programme.

(2.2) Financial Limitations

The Kariba scheme has been planned in two stages, the first of which has an installed capacity of 600 MW and is estimated to cost some £80 million. The cost of the complete scheme with 1 200 MW is estimated at some £113 million. The importance of minimizing expenditure, especially in the early stages, needs no emphasis, and in consequence a number of economy measures have necessarily been adopted in the design of the system. Details are discussed in later Sections.

(2.3) Topography

A great deal of the plateau territory covered by the lines and substations is veldt-land, the vegetation being mainly coarse grass and bush, consisting mostly of small trees which can be cleared by the heavier tracked type of bulldozer. In the northern section large anthills and many small swamps, known as *dambos*, are encountered. The *dambos* dry out in the winter months but become waterlogged in the wet seasons, and are avoided for tower locations wherever possible. There are large outcrops of rock, which in some areas is micacious and of high resistivity.

There has been no difficulty in finding level sites for substations, but for the switchyard at Kariba it has been necessary to level a site near the dam at considerable cost.

(2.4) Climate

Although it lies wholly within the tropics, Rhodesia enjoys a fine dry climate for most of the year. During the four months from mid-November to mid-March there are heavy rains, often accompanied by violent thunderstorms. These storms are not continuous, but each may last several hours, often interspersed with sunny periods. The rainfall is heavy and concentrated, the annual average being 25–30 in, with local variations of up to twice this figure.

(2.5) Transport

The railway, which is of 3 ft 6 in gauge and mainly single track, links the main centres and joins them to neighbouring territories. Until recently the principal route for heavy goods was via the port of Beira in Mozambique (Portuguese East Africa), but there is now a link to a second Portuguese port, Lourenço Marques. There are direct rail links from the north to the port of Lobito and from the south to the railway in the Union of South Africa. The internal railway axle-load limit and loading gauge are less than those in the United Kingdom, and the railway is heavily loaded with mineral traffic. These factors set limits to the size and weight of plant for the system, and affect the programme of construction.

The quality of the roads in Rhodesia varies from place to place and from time to time. All-weather highways connect Salisbury, Bulawayo and other centres in the midlands of Southern Rhodesia, and a fair road runs from Salisbury to the copper belt via Chirundu and Lusaka. Elsewhere the roads are mainly unmetalled and may be impassable in the wet season.

Most plant for Kariba must be transported 150 miles by road from a railhead. Special vehicles have been obtained to carry the heaviest parts, and new or reinforced roads have been constructed.

Spurs from the main Salisbury–Lusaka highway have been constructed to Kariba on each side of the river, linked by a temporary bridge which will be replaced later by a road across the dam itself.

(3) SYSTEM DESIGN

(3.1) Interconnection with Existing Undertakings

Power from Kariba is required in areas already served by undertakings owning thermal generating stations. The main features of these systems are shown in Table 2.

Table 2

Some Salient Features of Existing Systems

	Rhodesia Congo Border Power Corporation	Salisbury Corporation	Southern Rhodesia Electricity Supply Commission	Bulawayo Corporation
Total generating capacity, MW	200	156	166	147
Capacity of principal generators, MW	1 × 16 5 × 15	2 × 30 2 × 20	5 × 20	3 × 30 2 × 15
Main supply voltage, kV	66	33	88	33

From an administrative point of view the operation of the public electricity supply industry in Rhodesia was simplified by the 1956 Act, which gave the new Federal Power Board authority to regulate the integrated system in addition to supplying energy in bulk from Kariba. Under the Act the Board is given powers, on extending its transmission system to form an interconnection with any licensee or local authority, to direct the subsequent operation of the local generating plant. Thus the position will be similar to that under the former Central Electricity Board in Great Britain, the licensees or local authorities becoming the equivalent of selected station owners, who continue in ownership of their power stations (and, of course, their distribution systems) but for operational purpose come under a load-dispatching organization controlled centrally by the F.P.B.

Owing to the cost of e.h.v. step-down stations it is necessary to deliver power to the receiving areas in large blocks at a limited number of points. In the north, Kitwe is the focal point of the 66 kV system and is already the receiving station for the existing 220 kV link with the Belgian Congo, and so it was clearly the correct receiving station for the new system. In the south, points of supply near Salisbury and Bulawayo were obviously necessary, as also was a point close to the largest Electricity Supply Commission (E.S.C.) steam station, Umniati. A westerly connection with the E.S.C. has been combined with the Bulawayo supply at Marvel substation, but an easterly connection has required a separate substation at Norton, about 23 miles from Salisbury. To reduce the initial cost of switchgear the supply to Salisbury itself is being given over transformer feeders controlled at Norton by the same circuit-breakers as the local transformers.

The location of these points of bulk supply naturally delineates the system to a large extent. Provision for future expansion has been made by making minor deviations in line routes, e.g. near Sinoia, Gwelo and Lusaka.

There seems little possibility that the generating capacity of

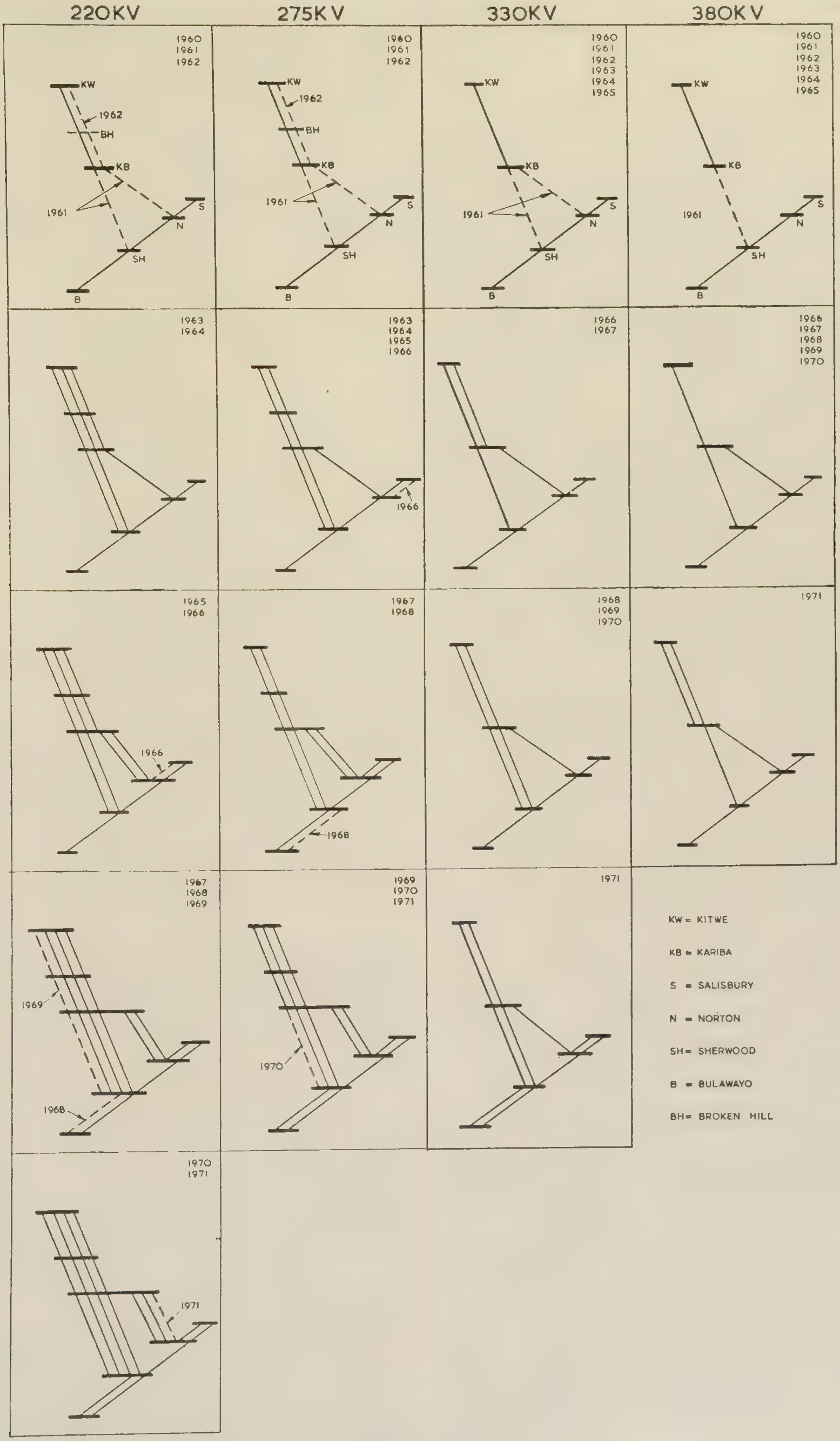


Fig. 2.—Development of systems at various voltages (see next page).

any existing thermal station will exceed local needs once the e.h.v. scheme is in operation, so that the receiving stations cater only for power imports.

(3.2) Choice of Voltage

Several transmission voltages already in use elsewhere would be suitable for the powers and the distances concerned. The early project reports, based on rather less peak output, proposed the use of 220 or 275 kV. It was decided to compare schemes at four voltages, 220, 275, 330 and 380 kV. To make a detailed technical and economic comparison of such schemes covering the period of development of the project would have taken 12 months or more. Unfortunately little time was available for this part of the work if construction were not to be delayed. Consequently a straightforward type of comparison was necessary and many interesting refinements had to be omitted or left for later study.

The general configuration of the system is dictated by the location of the nodal points and the advantage of using routes near existing roads or railways. Accordingly the schemes at the different voltages studied differed in the numbers of circuits, the amount of intermediate switching facilities, and reactive control plant, but employed the same general layout. The voltage selected is a compromise between initial and ultimate requirements of load carrying, security of supply, maintenance of stability, good lightning performance and cost.

Early system studies showed that the limits set to the transmission of power by the possibility of transient instability were low enough to control the development of the system at some stages. A series of stability studies was made using a common basis of power demand, system layout and assumed plant characteristics which led to the schemes of development at the four voltages shown in Fig. 2, in which transmission lines were added as the power reached the calculated limit of each stage.

An outline of the basis of these studies may be of interest. For simplicity of initial analysis the total load at any stage was assumed to be divided equally between four consuming centres, and concentrated at the l.v. terminals of the step-down transformers. In comparing the performance of the systems at the four voltages the loads were represented as impedances, the effect of live loads being considered separately, as was the unequal division of load predicted by the estimates.

Lines for all voltages were assumed to have twin steel-cored-aluminium conductors, the sections investigated being 0·175, 0·25, 0·35 and 0·6 in^2 copper equivalent. All transformers were assumed to be single-phase units having bank ratings in the region of 90 MVA, and having a normal reactance from high to low voltage; tertiary windings for reactive control were assumed. The Kariba generators were then 77 MW units, although the rating was raised later; the reactances and inertias assumed were typical of plant of the type concerned. Protective gear giving an operating time of 0·06 sec and circuit-breakers having a total break time of 0·06 sec at all currents gave a fault duration of 0·12 sec for use in formulating the transient stability criterion. The major comparison was therefore based on data that represented good equipment obtainable at normal prices. Subsidiary studies were made to indicate the benefits to be expected from the use of equipment having unusual characteristics such as low reactance or high inertia.

It was considered unrealistic to design the system to withstand the effects of a 3-phase fault on a major line, as such faults should be rare with the configuration and spacing assumed. Stability limits were therefore based on a double-line-to-earth fault.

The single lines initially supplying some centres obviously have zero stable power limit unless auto-reclosing is used. Even so, the limit is very low with triple-pole reclosure, irrespective of the nature of the fault. For the single radial lines the criterion used for comparisons was a fault at a substation on an adjacent feeder. The justification for the use of single-circuit supplies, including the question of single-pole reclosure, is discussed in Section 3.3.

The systems found satisfactory in the stability studies were checked for loading and voltage regulation and the reactive control plant required was determined. The relative capital costs over the construction period were then estimated, with the results shown in Fig. 3. This comparison shows that a 330 kV system is somewhat more costly initially but has substantial financial advantage by the end of the development, compared with 275 and 220 kV schemes. The 380 kV scheme was substantially more costly initially, and as initial capital limitation was one of the governing factors this voltage was therefore ruled out. It was considered that the future advantages of the 330 kV scheme outweighed its small starting handicap sufficiently to make this the right choice of voltage. More detailed studies were then made to decide many of the plant characteristics for use in the tender specifications.

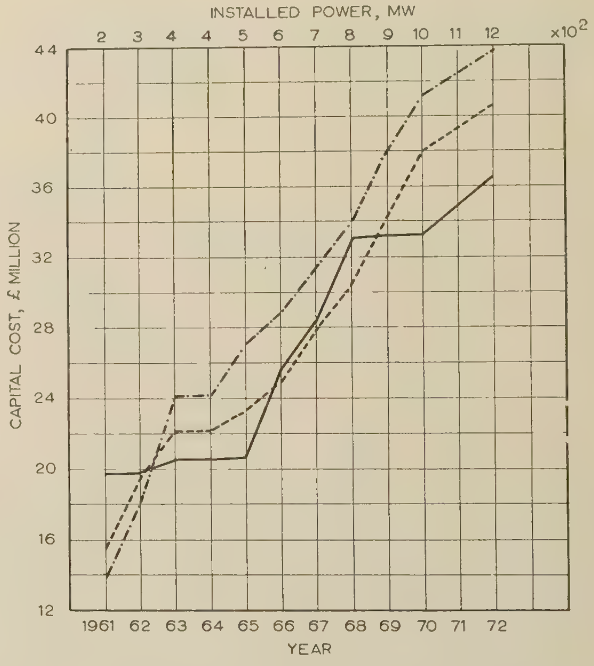


Fig. 3.—Comparative capital costs of transmission systems.
—·— 220 kV.
---- 275 kV.
—— 330 kV.

Following the receipt of tenders, and especially after the contracts had been placed for the first phase of development, it was possible to make revised and more detailed studies on a firmer basis of system data and estimated loadings. These have led to some modifications in the plans for the second phase of construction. Two changes which have also led to improvements in the first phase are

(*a*) The routes finally selected for construction of the lines in Southern Rhodesia are appreciably shorter than the estimates.
(*b*) Revised estimates of load show a swing north-east.

As a result the stability and cohesion of the system as a whole should be slightly better than was expected when contracts were placed.

(3.3) Security of Supply

In the early stages of a large new hydro-electric development it is difficult to obtain sufficient revenue to cover the charges on the heavy initial capital investment. This fact, together with the transmission distances concerned, made it obvious that only a few lines could be contemplated at any of the possible service voltages. Supply to some centres would have to be given over single circuits in the first few years—a situation that is unusual in major supplies in Europe. While security equal to that of a duplicate supply could not be expected, nevertheless the standard required would have to be much better than that associated with single rural distributors at lower voltages.

In consequence, much attention has been given to reducing the risk of outages due to instability, lightning faults and apparatus failures, and at first there will be less freedom in operating practice than is possible in extensively interconnected systems.

(3.3.1) Single-Pole Auto-Reclosing.

Faults on the 330 kV system are expected to be predominantly of the single-line-to-earth type, so that any means adopted to reduce the chance of outage due to such a fault would improve the security of supply appreciably. One such means is single-pole automatic reclosure. Stability studies using single-pole switching on the Kariba–Kitwe and Sherwood–Bulawayo lines gave limits greater than those set by other factors to the transmission of power over single circuits on these routes, and so it was decided to use single-pole auto-reclosure on these lines.

Single-pole auto-reclosure has been much discussed but little used at very high voltages. Its most favourable application is to single-circuit lines supplying important loads that cannot support the costs of a duplicate feed for several years, as in this case. The gear to give a single-pole trip and reclose followed, if required, by triple-pole trip and lockout is complicated and involves a risk of inadvertent single phasing, but the greatest doubt relates to the likelihood of the fault arc-path deionizing in a short enough time. Field tests have been made at voltages up to 400 kV[7,8,9] and laboratory tests at 132 kV. Additional laboratory tests were made on a 330 kV basis at the authors' instigation.[10] The sum of such evidence is far from conclusive, but it tends to show that a deionizing interval of 0·3 sec should be ample when switching 330 kV lines up to 150 miles in length, and that there is a good chance of success with an interval of 0·5 sec even when opening the line from Kariba to Kitwe—a length of 270 miles if no sectioning circuit-breaker is introduced. Field tests will be conducted during commissioning, and the results obtained in service will be of great interest.

The recent decision to provide a tapping point at Lusaka has required the installation of a line circuit-breaker on this site, thus dividing the Kariba–Kitwe line into two sections. Although this section point is only 90 miles from Kariba, it is believed that the capacitive current in the remaining 180 miles to Kitwe will be insufficient to maintain ionization of fault arc paths.

(3.3.2) Intermediate Switching Stations.

With few lines, and line lengths such as 200–270 miles a large increase in system impedance obviously occurs if a line trips on a fault or is opened for maintenance. Intermediate switching stations would improve both the dynamic performance of the system and its ease of maintenance, but they are costly and require economic justification.

The increasing use of electricity in the future made possible by the hydro-electric power is expected to require new points of supply, and Sinoia and Broken Hill are two likely tapping points which are also suitable switching centres.

Comparative studies were made to determine the plant required at each stage of system development with and without intermediate switching at these points. The extra cost of the switching stations was found to be slightly less than the corresponding reductions in reactive-plant requirements and in postponed line construction. The stations would, in fact, have been justifiable even against some adverse balance of capital cost, although the improvement in operation and maintenance is difficult to express in accounting terms.

The system planned as a result of the foregoing studies is shown in Fig. 4.

(3.4) Lightning Performance

Kariba lies near the centre of one of the worst lightning areas in the world. Although the isoceraunic level is a dubious guide

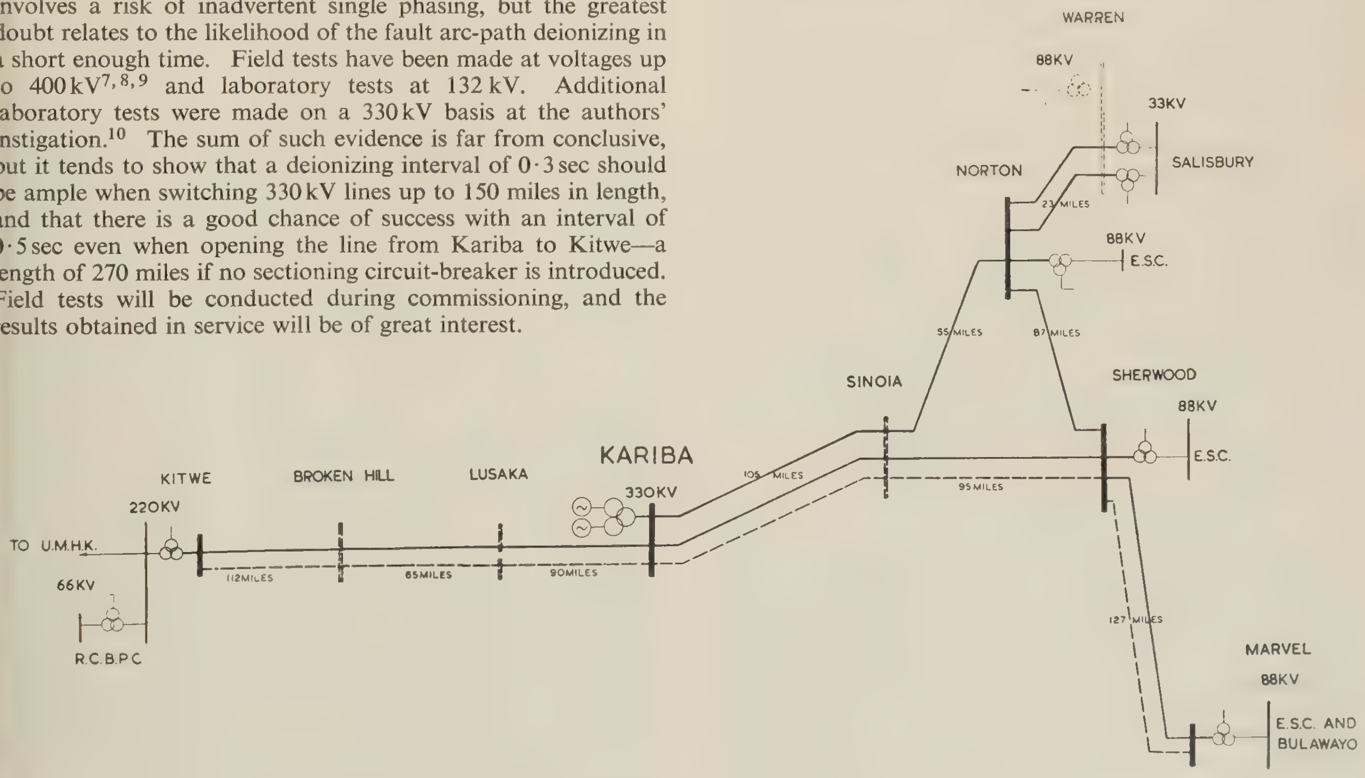


Fig. 4.—Diagram of 330 kV system.

——— Construction of first phase.
- - - - Construction of second phase

to the likely frequency of lightning strokes to an overhead line, it is the best available in such virtually virgin territory. Levels up to 120 have been reported, and meteorological records quoted by Brooks[11] show an incidence of 30–40 for lightning strokes to ground per square mile in Rhodesia. For Africa this corresponds to an isoceraunic level of about 90. In such conditions it is normal practice to use double overhead earth wires to reduce the probability of a direct stroke to a conductor to a negligible value. Induced surges in e.h.v. systems can be ignored, so that back-flashovers due to direct strokes to earthed metal remain to be considered.

The probability of such flashovers can be calculated approximately, and the results of calculations for typical lines are shown below. These figures are probable rates per 100 miles per annum and were estimated for typical lines of flat spacing based on an isoceraunic level of 60 and footing resistances of 20 ohms, account being taken of site altitude; the estimations were based on conventional theories originated by Bewley.[12]

Service voltage kV	Number of flashovers per 100 miles per annum
220	1·6
275	1·1
330	0·8
380	0·4

The probability of back flashover rises rapidly with increasing tower footing resistance, typical values for 330 kV being as follows:

Footing resistances (assumed uniform) ohms	Number of flashovers per 100 miles per annum
20	0·8
50	5·0
100	16

The terrain is varied and rocky in parts and resistances of more than 300 ohms have been measured at certain tower positions; high resistances in Rhodesia have also been reported in an extensive study by Anderson and Jenner.[13,14] To reduce the probability of lightning faults to an acceptable level the lines are being partly equipped with counterpoises (see Section 5.3.5).

When more than one circuit follows one route it is necessary to consider the probability of more than one circuit being affected at once. The much greater risk of this on double-circuit lines, enhanced by the effect of increased tower height, particularly where footing resistances are high, was considered such as to make double-circuit construction unacceptable. Consequently the lines will be of flat configuration on single-circuit towers with double overhead earth wires. The total number of lightning faults on all lines also affects the likelihood of transient instability occurring. This is obviously less the higher the service voltage; thus more circuits at a lower voltage do not necessarily give the increased security that mere numbers might suggest.

(3.5) Insulation Levels

The line insulation level other than at terminations is governed mainly by the 50 c/s wet withstand voltage, since an increase in insulation does not produce a proportional improvement in lightning performance on lines of this class. The 50 c/s voltage requirements lead to impulse flashover voltages ranging from about 1 350 to 1 450 kV, depending upon altitude, for insulator strings fitted with arcing horns at the line end only. Horns at both ends of the insulator strings have been used at all line terminations to limit the impulse flashover voltage to 1 250 kV. Since the loss of a transformer would be very serious, especially in the early stages, the transformer impulse withstand voltage has been specified as 1 350 kV. The insulation level of the 330 kV substation switchgear is similar.

To provide freedom of choice of 330 kV switchgear, the maximum permissible switching over-voltages were specified as 750 kV (peak) for interruption of capacitive currents and 1 050 kV (peak) for low inductive currents. Owing to the considerable length of the lines and the reactive loadings of the transformers, the range of each of these currents to be switched is unusually great and the voltage limits are fairly onerous. The circuit-breakers actually chosen are expected to give switching over-voltages of less than 600 kV on either duty, on the basis of tests made on generally similar circuit-breakers.

The transformers are protected by surge diverters so selected that they will not spark over on these switching over-voltages, whilst their impulse sparkover and discharge voltage characteristics give an adequate margin of protection to the transformers.

(4) SYSTEM CONTROL

The Kariba system approaches the classic example of an isolated hydro-electric station supplying remote load centres, and some of its problems have a textbook flavour; their economics are severely practical. The means adopted for system control, and some of the reasons for their adoption, are discussed in this Section.

(4.1) Load Flow

The load-forecast surveys made by the receiving undertakings included estimates of their future power factor, load factor and minimum load, as follows:

	Copper belt	Salisbury area	Central South area	Bulawayo area
Power factor ..	0·85	0·95	0·95	0·9
Load factor ..	0·65	0·48	0·56	0·47
Minimum load ..	0·50	0·20	0·33	0·25

The power factors were regarded as high enough to be accepted without special correction; the undertakings will be expected to ensure that much lower factors do not occur at peak load, or much higher ones at light load.

To provide control of the 330 kV system voltage, and ensure that power can always be delivered to the substation l.v. busbars with reasonable regulation, all step-down transformers are equipped with on-load regulating equipment and with tertiary windings for reactive control. Initially the problem will be to keep the voltage down to about the nominal value, owing to the large charging current of nearly 900 miles of 330 kV line, but later, of course, heavy load will lead to voltage drops.

In principle, it is possible to obtain sufficiently close control of the voltages on both h.v. and l.v. systems by means of either reactive control or tap changing. However, analyser studies of the proposed schemes showed that the use of both measures would lead to a better and more economical system. The best economy was obtained by providing a tap range of 20% (a normal design) and using this range to minimize the reactive-plant capacity. Consequently the first transformers will be loaded with 20 MVAr reactors switched on the tertiary windings, while two 40 MVAr units will be used at Kariba to supplement the under-excited capacity of the machines. Later step-down transformers will carry synchronous compensators and possibly some static capacitors. The system planned will transmit the full capacity of the A Station (600 MW) before any synchronous compensators are needed. The control provided will enable the voltage rise at light load on the 330 kV lines to be restrained to about 10% and will enable synchronizing voltages to be matched to within a few per cent. Nevertheless the switching of lines will require care, since the imposition of the charging current of a long line on one of the receiving areas could lead to dangerous over-voltages. Lines must be 'picked up' initially from the

Kariba end with their terminal transformers and reactors connected, the synchronizing being done on the l.v. side.

If the line or transformer circuit-breaker at Kitwe should open, thus removing the restraining effect of the terminal transformers and reactors, the open end of the line might be subject to a power-frequency over-voltage of about 30%. This will occur momentarily during the clearance of some faults, but the switching operations that would lead to the voltage being sustained should not normally occur. Conditions on the Kitwe line are potentially the worst as this line is much the longest.

(4.2) Effect of Interconnections

The more modern steam plant in the receiving areas will remain running in parallel with the F.P.B. system, supplying part of the local load and providing limited standby.

Co-operation between the F.P.B. and the receiving authorities should be technically straightforward except in the copper belt. Here the copper-belt system is already linked to the Union Minière de Haut Katanga (U.M.H.K.) system in the Belgian Congo by a long 220 kV line. Originally this link was planned to last only until 1965, but local developments at 220 kV are now being planned for the copper belt. It seems possible that at least a standby tie with the Belgian Congo will exist for many years. The interconnected system so formed will have a length of about 1 000 miles, including one or two rather weak links, and interesting operating problems will arise.

At present the Rhodesia Congo Border Power Corporation (R.C.B.P.C.) has a control centre in Kitwe, and the U.M.H.K. has one in Jadotville, which regulate the combined operation of their respective systems. The Kitwe control will become a major satellite of the F.P.B. control centre, and will form a vital link of communication between Rhodesia and the Belgian Congo. The experience now being gained in operating the 220 kV link will lay a foundation for the combined 330/220 kV operations to follow.

(4.3) Central and Local Control Scheme

The F.P.B. main control centre will be located at Sherwood with manned subsidiary controls at Kariba power station and at Kitwe, Norton, Salisbury and Marvel (Bulawayo) substations. Communication and indication will be obtained by means of a combined voice-frequency telegraph and power-line carrier system; separate carrier-current equipment is employed for protective purposes.

In the central control room, indications will be given of all circuit-breaker positions, of the state of certain isolators, of limiting tap positions and of the voltage, power and reactive flow in the lines and the principal circuits at the substations. The load of the thermal generating stations in the receiving areas will be summated locally and indicated centrally by hand dressing of the panel, as will the positions of the majority of the isolating switches. The substations will be controlled locally by light-current direct wire from the attended point.

The layout of the central control room follows normal practice. A double desk in the centre of the room will accommodate a load dispatcher and a switching engineer, a double system diagram panel giving the principal system information required by each, i.e. the loading of the principal circuits and the state of the system connections, respectively. Other panels carry the frequency meters and chart recorders.

(5) STATIONS, PLANT AND EQUIPMENT

This Section deals only with those features of the plant and equipment which are important from a transmission point of view, and is therefore by no means exhaustive.

(5.1) Generating Stations

(5.1.1) General.

There are four principal thermal generating stations in the copper belt and three in the midlands, the total installed capacity and the ratings of the more modern sets being given in Table 2. There is also a wide variety of plant in small local stations, which would be expected in a rapidly developing country.

At Kariba there will be two generating stations. The first is being built in a cavern hewn out of the rock of the right bank of the gorge, and will contain six 100 MW machines. The planning of the project assumed the construction of a similar station in the left bank, but, in fact, it is probable that the 'B' station will be larger.

(5.1.2) Kariba Station Arrangement.

The 'A' station comprises two main chambers with connecting tunnels; the larger contains the generating sets with their switchgear and the smaller contains the step-up transformers, 330 kV surge diverters and the shunt-compensating reactors with their switchgear.

The generators are connected to their step-up transformers in pairs as shown in Fig. 5 (on next page) and each of the two 40 MVAr reactors can be connected to either of two step-up transformers. The 18 kV switchgear is of air-blast type, the generator circuit-breakers being rated at 1 500 MVA and the two reactor circuit-breakers at 2 000 MVA.

The arrangement of the Kariba 330 kV switchgear shown in Fig. 5 is similar to that of the substations and is therefore discussed in Section 5.2.

(5.1.3) Generators.

The generators are each rated at 100 MW, 111 MVA, 0·9 power factor, 18 kV, 167 r.p.m. They are of the umbrella type driven by Francis turbines designed to give full load at heads down to 282 ft. Further technical details are given in Table 3. The first two machines will be run from temporary low-level intakes to give a supply before the completion and filling of the dam; these arrangements are expected to provide an output of at least 30 MW from each machine.

Table 3

PARTICULARS OF KARIBA GENERATORS

Rated Output 100 MW 0·9 Power Factor at 18 kV

Inertia constant	5 kWs/kVA
Overspeed ratio	1·92
Direct-axis synchronous reactance	70%
Quadrature-axis synchronous reactance	40·5%
Direct-axis transient reactance	24%
Direct-axis sub-transient reactance	15%
Negative-sequence reactance	18%
Zero-sequence reactance	13%
Short-circuit ratio	1·75
Open-circuit transient time-constant	9 sec
Short-circuit transient time-constant	3 sec
Exciter response rate	2 sec^{-1}

Since stability was one of the governing factors in the system design, it was obviously important to minimize the impedances of all plant. Accordingly the transient reactance specified for the generators was the lowest for which it was believed an economic design could be produced. For the same reason an inertia somewhat larger than normal has been employed, the aim being to obtain the highest value given by greater weight without increasing dimensions established by other design criteria.

The machines will normally operate at leading power factor, and full rating is required at zero power factor for line charging;

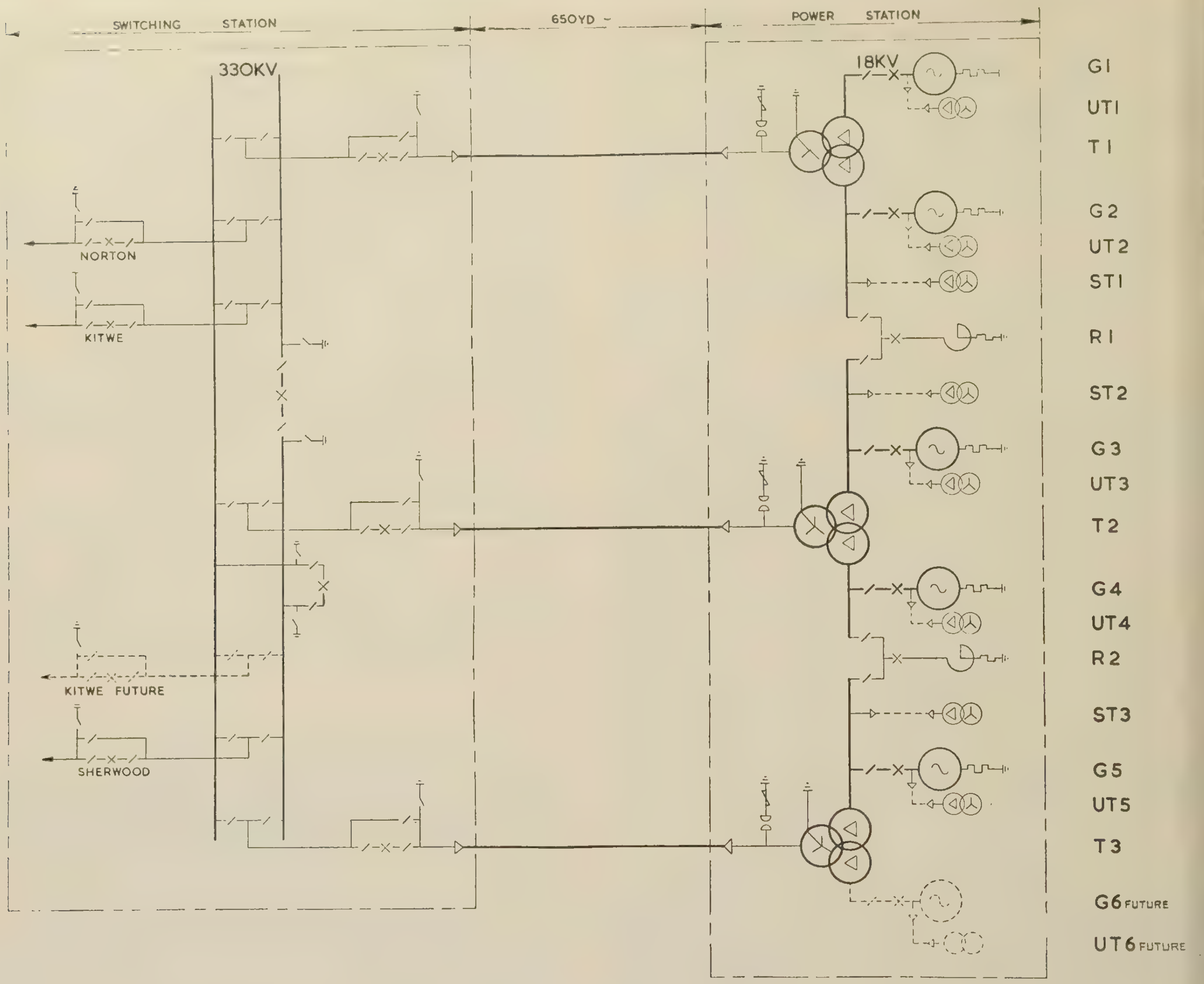


Fig. 5.—Schematic of Kariba power station.

only if a major line is out of service at peak load will the power factor become lagging. Prolonged operation at leading power factors led to the choice of a low synchronous reactance and a fast excitation system. The low synchronous reactance enables the full rating of the machine to be obtained at zero leading power factor, and, in conjunction with the fast excitation, provides adequate dynamic margins. The faster response obtainable from a separately driven exciter was not necessary, and the more reliable direct drive was therefore chosen.

The steady-state capability of a generator alone is illustrated in Fig. 6(*a*). This chart applies to a machine operating at rated voltage on an infinite busbar at its terminals, the dynamic effect of voltage-regulator action being neglected. Additional limits are given for 90% voltage at leading power factors and 105% voltage at lagging power factors. It will be seen that a substantial margin of stability in the under-excited zone is apparently available.

However, charts drawn on these assumptions do not apply to a long transmission system. The effect of the system is illustrated typically by Fig. 6(*b*), which is drawn for constant rated voltage on the Kariba 330 kV busbars and with the system included up to the substation l.v. busbars assumed to be infinite for power but variable in voltage. The stability margin is substantially less than in Fig. 6(*a*), and, although it would be increased somewhat if the dynamic action of the voltage regulators were included, it is clear that charts of the Kariba machines alone must be used with caution.

(5.1.4) **Transformers.**

Transport limitations made the selection of the type of generator step-up transformer difficult. The transformers selected consist of three single-phase units of ratio 191/18/18 kV rated 80/40/40 MVA and connected Y*dd* with solidly-earthed neutral. The low voltage was arranged to suit the generators, and no tappings are provided since the generator voltage range is wide enough to make them unnecessary. The reactance from each l.v. winding to the h.v. winding is 12·5% on 120 MVA, that between l.v. windings being 25% so as to limit the short-circuit duty on the 18 kV switchgear. Cooling is by water tapped from the penstocks. One spare phase is provided for the 'A' station.

The choice of single-phase transformers of this rating was

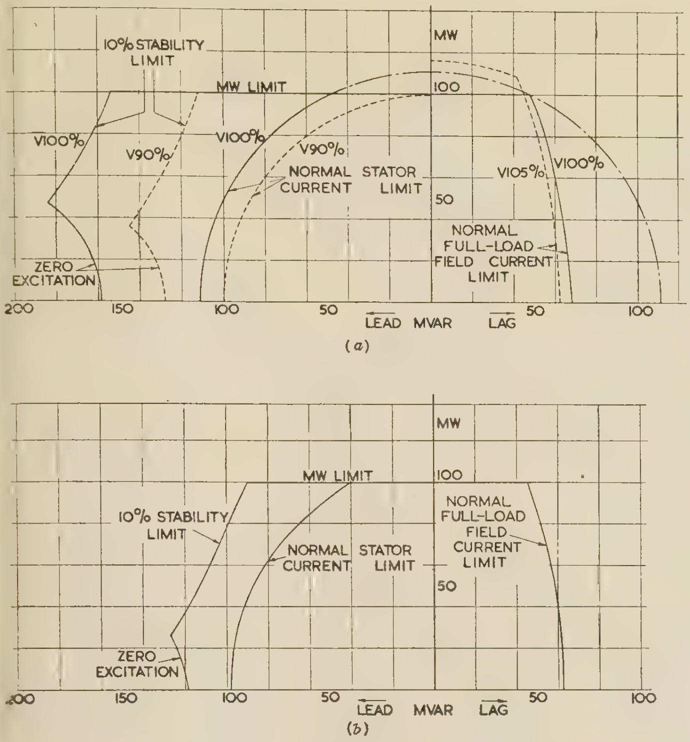


Fig. 6.—Capability charts.

(a) Generator on an infinite busbar at its terminals. Additional limits are given for 90% and 105% voltage.
(b) Generators connected to the system. (Chart for one machine of four in use.)

influenced by the fact that complete 3-phase transformers for 120 MVA could not be transported to the site, and site assembly was considered undesirable.

(5.1.5) 330 kV Cables.

The transformers are connected to the switchgear by means of 330 kV single-core oil-filled lead-covered cables of $0\cdot85\,in^2$ copper cross-section, insulated for an impulse level of $1\cdot5$ MV and stressed to 110 kV/cm at the conductor surface. These cables are cleated in flat formation to racks in sectors of a shaft 22 ft in diameter running vertically for 500 ft above the power station.

(5.2) Substations

(5.2.1) General Arrangement.

The shell arch dam at Kariba and the underground power station offer no foothold for a 330 kV switching station, and the least unsuitable site is the summits of two adjacent small hills in the irregular country above the gorge almost directly over the power station. Equal cutting and filling has joined the two hilltops in a stepped area forming two rectangles joined at a slight angle, on which it has been possible to accommodate a double-busbar station with sufficient bays for the projected development using a particularly compact switchgear layout developed for the purpose. Part of the station is shown in Fig. 7 (on next page).

The 330 kV switchgear is of the low-level type incorporating the following features leading to reduced area:

(a) Bay width is reduced by using vertical-blade isolators instead of the horizontal-blade type.

(b) Bay length is reduced by using a higher level than usual for the busbars, bulk-oil circuit-breakers with integral current transformers, and mounting the by-pass and one circuit isolator on the same structure, one upright and one inverted.

The extra cost of the slightly higher structures is far exceeded by the savings in civil-engineering works, foundations, main and earth connections, auxiliary cables, pipework, fencing, etc.

At the outlying substations the importance of restricting the site area is much less. However, the Kariba arrangement was considered suitable for general application, and as uniformity of layout is desirable, the same scheme was adopted as a general standard for the substations. The arrangement of a transformer bay is shown in Fig. 8 (page 591). All 330 kV connections are of single-conductor stranded aluminium of $2\cdot85\,in^2$ cross-section and overall diameter of $2\cdot2$ in with compression joints and connectors.

Lightning protection of the substations is provided by masts 65 ft high superimposed on the substation structures, themselves $72\frac{1}{2}$ ft high. Exceptions are the small site at Salisbury, where overhead wires were more convenient, and Kariba switching station, where free-standing masts 200 ft high are used. The risk of a back flashover of substation insulation associated with structure-borne masts is estimated to be extremely small, but owing to the serious disturbance that would follow a busbar fault at Kariba, it was thought wise to eliminate all risk of such a flashover there. The protective areas afforded by the masts were determined by reference to model tests and certain existing installations; they are illustrated by the chain-dotted lines in Fig. 7.

Where ground conditions permit it is intended to earth the substations in a normal manner by driven rods and copper-strip bonding. Where difficult conditions are encountered it will be necessary to resort to buried earthing meshes.

(5.2.2) 330 kV Switchgear.

The 330 kV circuit-breakers are rated at 7 500 MVA at 330 and 363 kV on both normal British Standard and 3-pole auto-reclosing duty. The rates of rise of restriking voltage specified for the 100% symmetrical and 10% duties are 3 and 8 kV/microsec, respectively, and the circuit-breakers have to be capable of interrupting charging currents of up to 300 amp and magnetizing currents of up to 200 amp without generating excessive over-voltages. An unusually comprehensive series of proving tests has been specified to cover all switching conditions likely to be encountered in service.

The circuit-breakers selected are of the bulk-oil lenticular-tank type using six breaks per phase, each shunted by a linear resistor, with six auxiliary breaks to interrupt the resistor current. The novel arrangement of the breaks is illustrated in Fig. 9 (page 591) in which the current paths when the circuit-breaker is closed are shown by the heavy lines. A single-cylinder pneumatic-operating mechanism drives all three poles of the circuit-breaker, except for those required for single-pole auto-reclosing duty, which have a mechanism on each pole.

The vertical-break isolators have a hinge mechanism which rotates the contact blade through 45° while engaged with the fixed contact, thus releasing the contact pressure before the arm begins to lift.

(5.2.3) Transformers and Reactive Plant.

In contrast to the transformers for Kariba, those for the substations are all 3-phase units. The largest rating of double-wound 3-phase transformer to come within the transport limits is about 60 MVA, which is a convenient rating to use singly for some early supplies and in banks for larger loads. A bank of single-phase units of the largest transportable rating, 60–80 MVA, would have been inconveniently large. Smaller single-phase arrangements were uneconomic.

In the south there are two low voltages, 88 and 33 kV, but all the transformers are otherwise similar. The winding arrange-

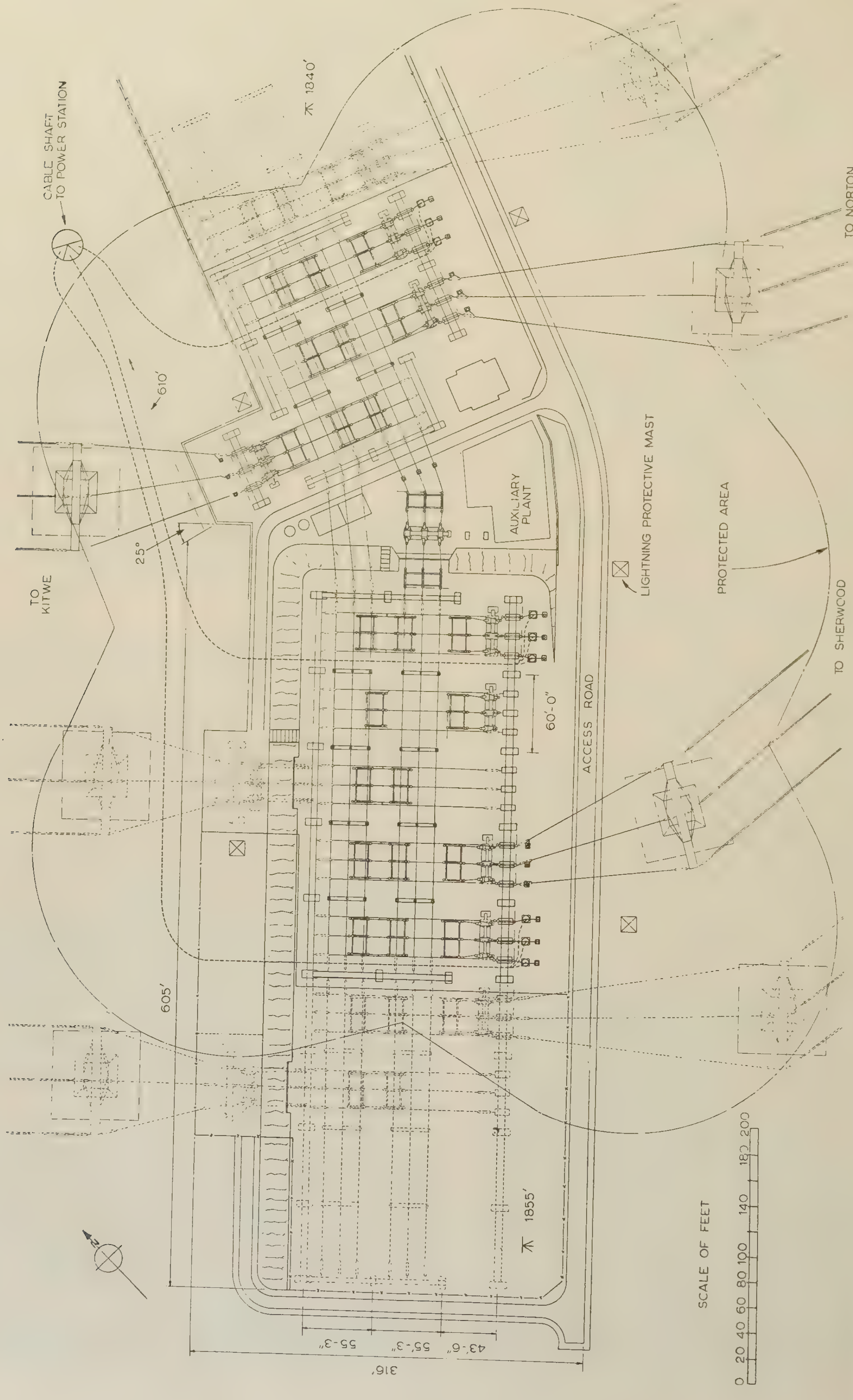


Fig. 7.—Layout of Kariba 330 kV switching station.
Height above sea level.

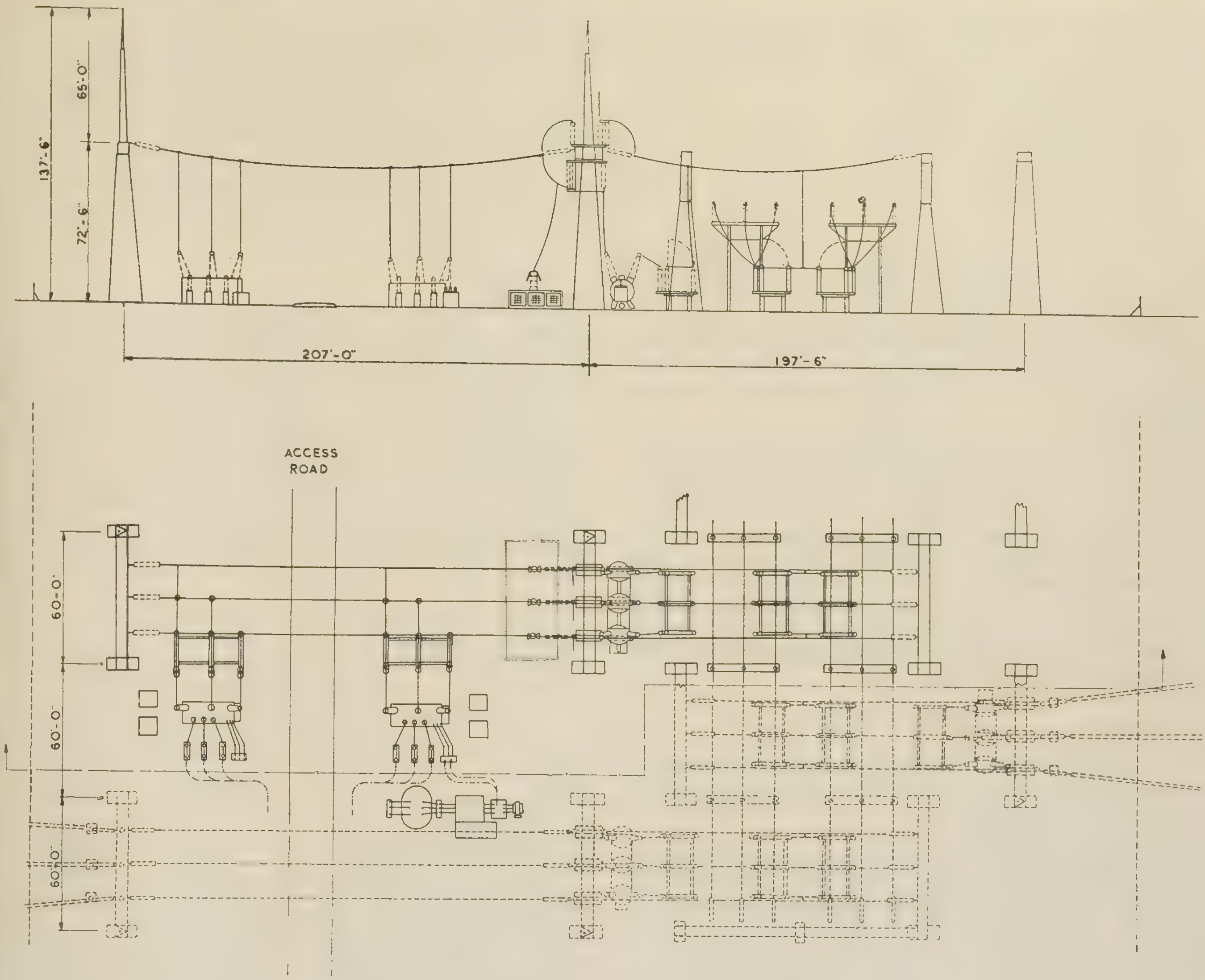


Fig. 8.—Arrangement of substation transformer bay.

ment is Y*yd*, the on-load tap changer of the high-speed resistor type being located on the l.v. side. Although provision has been made for the addition of automatic tap changing, the present view is that the greater complication of control equipment is unwarranted. Mainly on account of stability considerations a maximum value of 11% was specified for the reactance from high to low voltage. The windings are arranged to give the lowest interwinding reactance between the l.v. and tertiary winding, so that the reactive control is applied, electrically, as close as possible to the load. Mixed cooling is used. All tertiary ratings are one-third of the transformer rating, and small auxiliary transformers are connected to these windings to give local 380/220-volt supplies.

At Kitwe, power from Kariba is delivered to the 220 kV substation; most of the import is further transformed to 66 kV for distribution, but a part is transmitted at 220 kV to another substation further north. Owing to the relatively close ratio of transformation, auto-transformers have been adopted, and for this design the transport limits permit a 3-phase rating of 120 MVA to be used. To limit the size of the main units, and to avoid locating tappings at high voltage in these units, the ratio is regulated by a series booster on the 220 kV side, energized from the 11 kV tertiary winding on the main transformers. The

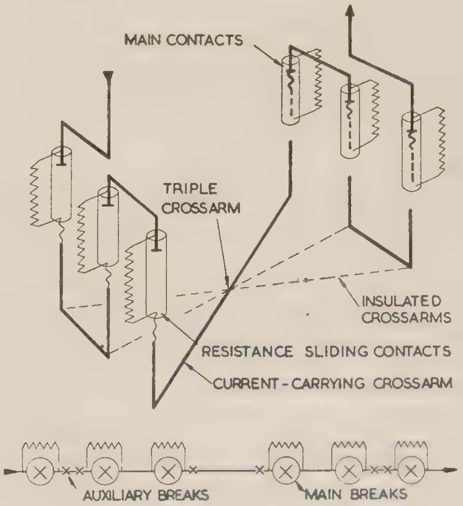


Fig. 9.—Arrangement of six breaks in 330 kV circuit-breakers.
Right-hand breaks show position of main arc.
Left-hand breaks show resistor arc after interruption of main arc.

reactance between h.v. and l.v. windings of the transformers is 8%, the booster contributing a further 2% approximately.

The other inter-winding reactances of the three types of transformer are approximately as follows:

Ratio of transformer	330/220 kV	330/88 kV	330/33 kV
Reactance (percentage on transformer rating)			
H.V. to tertiary winding	31	20·5	17·5
L.V. to tertiary winding	25	11	11

Throughout the first phase of the scheme the reactive control plant will comprise 20 MVA shunt compensating reactors which are of the iron-cored and oil-immersed type designed for a low noise level and capable of operating continuously at 10% above the rated voltage. The reactors are connected by 11 kV air-blast switchgear to the tertiary windings of the substation transformers.

The characteristics of the synchronous compensators required in the second phase of the system development have not yet been decided. Units of 20 MVAr rating will be connected to the tertiary windings of the transformers in the southern substations. At Kitwe there are already 20 MVAr compensators connected to the tertiary windings of the 220/66 kV transformers installed for the Belgian Congo link. Additional 220/66 kV transformers will be required for the supply from Kariba, and better parallel operation with future compensators will be obtained by locating all compensators similarly rather than by connecting some to the 330/220 kV transformers.

(5.3) Transmission Lines

(5.3.1) General.

As already mentioned, the better lightning performance of single-circuit lines with double shield-wires led to their adoption. Difficult earthing conditions required the use of counterpoises for substantial parts of the lines.

The choice of conductor was based on studies of the transmission capacity, resistance and corona losses, radio-interference level and cost associated with various numbers and types of conductor. It was concluded that two steel-cored-aluminium conductors per phase, each of 0·35 copper-equivalent cross-section, at 18 in spacing was, the economic choice; this solution is in general agreement with the conclusions reached in the design of other similar systems. Since the lines will supply the third largest copper-producing area in the world, the merits of copper conductors were considered. However, the greater cost and weight of copper conductors precluded their use.

So far as is practicable the lines are routed within reach of existing roads and railways, in order to facilitate access for maintenance and future tappings.

(5.3.2) Conductors.

The conductor selected is a standard type of steel-cored-aluminium conductor having 54/·118 in strands of aluminium with a 7/·118 in steel core.

The twin conductor spacing of 18 in in the span is reduced to 12 in at the suspension points in order slightly to reduce cross-arm dimensions, which are largely determined by the live metal clearances required. The flexible-ring type of spacer was chosen as being the most suitable for the conditions. The first spacer from each tower is located at 30 ft, the remainder being at intervals of not more than 250 ft.

The 'everyday' tension of the conductors will be approximately 5 000 lb, which is less than one-fifth of the ultimate strength; this, together with the use of Stockbridge vibration dampers at the rate of four per component conductor per span, should ensure absence of vibration trouble.

The earth conductors are galvanized steel, also strung so that the 'everyday' tension is about one-fifth of the ultimate, and Stockbridge vibration dampers at the rate of four per earth conductor per span will be used. The life of galvanized steel in Rhodesia is known to be good and the choice of any more expensive alternative could not be justified.

Extended stress/strain tests on the conductors were carried out in order to determine the variations in the modulus of elasticity so that appropriate allowance for 'settlement' could be made when stringing conductors.

(5.3.3) Insulators.

To withstand, under rain conditions, the power-frequency overvoltages already discussed, the suspension insulators consist of single strings of nineteen 10 in diameter discs spaced with their centres 5¾ in apart. Under test, the 19-disc insulator string gives a 1 min wet-withstand value of 680 kV at sea level, which is equivalent to about 600 kV at the mean altitude of the line. The impulse level at the average line altitude for the suspension strings is approximately 1 400 kV.

The insulator units are normally made of toughened glass, but porcelain is being used at certain places where experience has shown that glass insulators make attractive targets for rifles. Details of the insulators are given in Table 4. Each

Table 4

Particulars of Transmission-Line Insulator Made of Toughened Glass

	Suspension set	Tension set
Units	10 in dia. 5¾ in centres	11 in dia. 7 in centres
Units per string	19	18
Number of strings in parallel	1	2
1 min wet-withstand voltage:		
Arcing horn at live end only	680 kV	780 kV
Arcing horns at both ends	570 kV	698 kV
50% impulse flashover voltage, 1/50 microsec negative polarity:		
Arcing horn at live end only	1 555 kV	1 600 kV
Arcing horns at both ends	1 422 kV	1 450 kV

The above electrical characteristics are the approximate figures obtained from tests corrected to standard atmospheric conditions to B.S. 137.

tension insulator set is equipped with a turnbuckle adjusting device to permit a large degree of regulation of the tensions and sags of the components of the twin conductors.

For the general run of line, all insulator sets have arcing horns only at the live end; over all sections of line within one mile of a substation, arcing horns are fitted at both ends to reduce the impulse voltage level below that of the substation apparatus and thus to give a large measure of protection to the latter against high-voltage travelling waves originating elsewhere on the line. Corona tests have been satisfactorily carried out on the various insulator and conductor fittings, the specified level being 245 kV to earth.

'Low loss' (aluminium alloy) suspension clamps were considered as an alternative to the usual malleable cast iron. Comparative tests were done on samples of both materials, but it was found that the decreased losses of the former under any likely sustained conditions of line loading on the F.P.B. system were not such as to offset their higher cost.

To prevent the contamination of insulators by large birds, all suspension towers have uncomfortable-looking serrations bolted to the cross-arms at strategic positions.

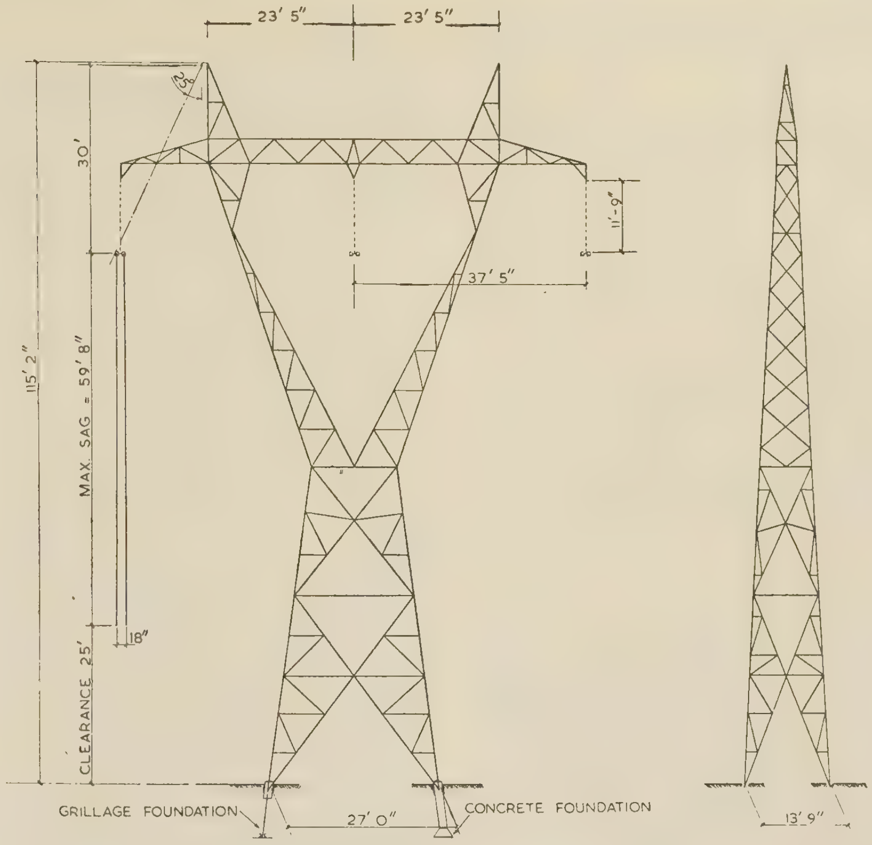


Fig. 10.—Outline of typical transmission tower.

(5.3.4) **Towers.**

Since 'economic span curves' are notoriously flat near their minima, it was decided to invite tenders based on a prescribed range of alternative standard spans, with the result that a standard of 1 500 ft was finally adopted. A free choice was permitted in the general outline of the tower design, the only specified dimensions being the ground clearance, the live metal clearances, and the line-conductor/earth-conductor separation and disposition. There was nothing in the specification to prohibit proposals for 'portal' type structures, but the conventional lattice-type waisted tower (see Fig. 10) was shown to be the most economical.

The tower types are straight-line suspension, 10° suspension angle, 10°, 30°, 60°, and 90° tension angle, terminal and transposition. All towers are constructed largely of high-tensile steel; the straight-line tower weighs approximately $6\frac{1}{2}$ tons. 10 and 20 ft tower-body extensions are available, and also a series of individual leg extensions from minus 6 ft to plus 12 ft, in steps of 3 ft, for use at side slope positions.

It is always debatable to what extent towers should be designed for broken-conductor conditions, especially in parts of the world where ice loading does not occur. Other possible causes of conductor breakage are remote but not negligible, and where single lines are to be relied upon for transfer of important loads over long distances, some margin of strength against unforeseen happenings is clearly desirable. Certain margins of longitudinal and torsional strength are also valuable for facilitating repair or replacement of conductors (without guying) and temporary or permanent line diversions.

The arrangement adopted is that all strain towers should be capable of withstanding the assumed breakage of any one complete phase of the line conductors, *plus* one earth conductor, all under maximum design tensions, but that suspension towers should be designed only for longitudinal unbalances corresponding to the 'everyday' tension in any one component (of the twin) line conductor or one earth conductor. That this longitudinal unbalance assumption on the suspension towers does not govern the overall design is illustrated by the fact that the tower bases are rectangular, with the short dimension in the line direction. The strain-tower bases are square. The designs of all the main tower types have been checked by full-scale prototype tests.

All lines except the very short (23-mile) section between Salisbury and Norton are transposed. The number and locations of the transposition towers have been selected to suit both the initial conditions and conditions when the intermediate switching stations and tapping points are constructed (see Section 3.3.2). The transposition towers are otherwise standard tension towers with special earth-wire peaks, between which is strung an insulator assembly to carry the over-running cross-connection between the two outer phases.

To avoid the rather heavy cost of concrete and its transport, the standard foundation for the straight-line tower is of the earth-grillage type, with an alternative concrete block foundation where dictated by ground conditions. All other types of tower have conventional concrete block foundations.

(5.3.5) **Counterpoises.**

Where footing resistances are found to exceed 20 ohms, a single 7/8 s.w.g. galvanized-steel continuous counterpoise will be laid from tower to tower; it is thereby hoped to keep the average flashover rate to 0·8, as discussed in Section 3.4. Over the last mile into every substation, a continuous double

counterpoise is being laid, regardless of tower-footing-resistance measurements, and will be connected into the main substation earthing system.

(5.3.6) **Line Characteristics.**

Tables 5, 6 and 7 summarize technical features of the design of the lines which are of interest. The total route length of line is 864 miles.

Table 5

ASSUMED DESIGN CONDITIONS AND FACTORS OF SAFETY OF THE TRANSMISSION LINES

Minimum conductor temperature	30° F
Maximum conductor temperature	150° F
Wind pressure on conductor projected area	9 lb/ft²
Wind pressure on 1·5 times the tower-face area	15 lb/ft²
Factors of safety:	
Conductors, towers and foundations under maximum working conditions	2·5
Towers and foundations under assumed broken-conductor or unbalance conditions	1·5

Table 6

CONDUCTOR PARTICULARS AND ELECTRICAL CHARACTERISTICS OF THE TRANSMISSION LINES

Line conductors	Twin, 0·35 in² (copper equivalent) steel-cored aluminium
Component conductor:	
Stranding	54/·118 in aluminium 7/·118 in steel (greased)
Overall diameter	1·062 in
Earth conductors	Galvanized steel 19/·104 in, 60 tons quality
Electrical characteristics of complete line:	
Resistance, at 60° F	0·061 ohm/mile
Reactance (50 c/s)	0·533 ohm/mile
Capacitive susceptance (50 c/s)	$5{\cdot}4 \times 10^{-6}$ mho/mile
Surge impedance	314 ohms

Table 7

PARTICULARS OF TOWER DESIGN

Minimum live-metal clearance, all towers	10 ft
Assumed insulator swing on straight-line towers at which the above applies	35°
Minimum ground clearance at 150° F	25 ft
Earth conductor maximum protective angle at all towers	25°
Earth conductor height above line conductors:	
At towers	30 ft
At mid-span, at 60° F, approximately	40 ft
Maximum slenderness ratio for tower compression members:	
Main members	120
Stressed bracings	200
Unstressed bracings	250
Minimum steel thicknesses:	
Main legs below cross arm	5/16 in
Main members in and above cross arm	1/4 in
Other stressed members	3/16 in
Unstressed members	1/8 in
Minimum bolt diameters:	
In stressed members	5/8 in
In unstressed members only	1/2 in
Standard tower-base widths:	
Straight-line tower	27 × 13·75 ft
10° suspension angle tower	29·25 × 13·75 ft
10° tension angle tower	24·25 ft square
30° angle tower	29·5 ft square
60° angle tower	33 ft square

(5.4) **Protection, Communication and Similar Equipment**

(5.4.1) **Protection.**

All 330 kV overhead lines, with the exception of Norton–Salisbury, which is a feeder transformer circuit, are protected by 3-zone high-speed distance protection using mho-type relays with carrier-accelerated tripping for faults within the second zone.

The Norton–Salisbury circuit is protected by single-zone high-speed distance protection covering the line and part of the transformer, together with coded carrier intertripping. In addition, definite-minimum-inverse-time back-up over-current and earth-fault relays are provided for each line.

Special blocking relays are provided to ensure that the high-speed distance protection will not operate under conditions of system instability, except at certain selected points determined from network-analyser studies. The design of the relay is such that, when tripping is allowed, it can only occur when the voltages at the two ends of the circuits are substantially in phase. This feature eases the duty on the line circuit-breakers by making it unlikely that they will be called upon to trip at a time when substantially more than the normal voltage would appear across them.

The protection of generators and reactors is conventional, consisting of overall differential protection with definite minimum-inverse-time back-up relays. Transformer windings are separately covered by balanced earth-fault protection with over-current relays for phase faults. Buchholz and winding-temperature relays are also employed on the transformers and Buchholz protection on the reactors.

(5.4.2) **Fault Location and Fault Recording.**

Each end of each 330 kV line is being equipped with special high-speed voltmeters and ammeters which are self-locking, thereby recording the zero-phase-sequence voltage and current at each end of each circuit during the brief interval of time between the occurrence of an earth fault and its clearance by the circuit-breaker. These will be calibrated on site, and by a simple calculation will enable the fault positions to be determined with fair accuracy.

Multi-element Masson-type disturbance recorders are being provided at Kariba, Sherwood and Norton, to give information concerning protective-gear performance and switch operation under fault conditions.

(5.4.3) **Communication.**

Main communication and control throughout the system is by superimposed power-line carrier working in conjunction with frequency-modulated voice-frequency telegraph equipment. Field radio employing a number of fixed and mobile stations is being used for communication with maintenance and repair gangs.

A direct carrier automatic telephone link is being provided between each station and the central control room at Sherwood, and, in addition, there is direct telephone communication over power-line carrier between some adjacent stations. There is a further direct telephone channel between the Head Office at Salisbury and the control room at Sherwood. In the event of complete failure of carrier on a line between two stations, there will be an alternative communication route, except on the radial circuits fed by a single line. In the first stage, however, there will be some restriction in the number of channels and standby facilities owing to the lengths and relatively small number of 330 kV lines.

Teleprinter communication is being provided between the central control and the attended point associated with each outstation, and facsimile reproducers are being installed at the Head Office and at the Central Control.

(6) CONSTRUCTION ASPECTS

(6.1) Programme

The major contracts were placed in July, 1956, and system construction commenced in February, 1957. Apart from the temporary use of the line between Salisbury and Bulawayo for the exchange of power from the thermal stations, the supplies from the system are expected to build up between January, 1960, and March, 1961. By the latter date four generators will be in commission, the fifth following in September, 1961; the date for the sixth is not yet fixed.

(6.2) Transport of Plant

The Federation of Rhodesia is mainly served by two Portuguese ports, Beira and Lourenço Marques, each of which is connected to the Federation by a single-track railway.

The maximum lifts that can be handled by the cranes at these ports are 20 and 80 tons, respectively, but it is expected that the majority of the equipment will be shipped to Beira since the rail haul is considerably shorter. Existing rail stock includes only two well wagons of 70 tons capacity and two of 25 tons capacity, although a further four well wagons of intermediate capacity may be available when traffic reaches its peak.

It was appreciated at the outset that the construction programme could not be maintained unless the delivery of the plant was carefully phased. Furthermore, it was decided that it would be necessary to purchase two wagons of 102 tons capacity each to transport the transformers, of which there are 24. These wagons will be used for the lighter plant when they are not in use for the transformers.

All heavy material will have to be shipped in vessels equipped with heavy lifting derricks, and the movement of the special railway wagons is being phased so that they will be available alongside on the arrival of the ships.

The railhead for Kariba power station is approximately 150 miles from the site. In view of the quantity of material to be handled at this railhead it was decided to install a 100-ton goliath crane to facilitate the unloading from the rail wagons and loading to road vehicles. The largest road trailer now being used in the Federation has a capacity of 70 tons, but a 100-ton trailer is being provided. The design of this trailer has presented problems as the tyre loading is restricted to 9 000 lb. Road transport for the heaviest lifts is possible only during a three-month period of the dry season.

The dimensions of the turbine runners make them the most difficult single piece of equipment for transport. Consideration has been given to both road and rail transport. Special brackets are being manufactured so that the runners can be accommodated on the 102-ton wagons, but road transport is to be preferred since the diameter of 13 ft 6 in compared with a permissible out-of-gauge loading of 13 ft 10 in leaves little margin for packing and protection. Further, since the present bridge on the Beira road crossing the Odzi river is inadequate, the river might have to be crossed by means of a ford. Construction of a new bridge is now planned and there is every possibility that it will be complete by the end of 1958.

(6.3) Line Survey and Bush Clearance

Suitable survey maps of the Federation were limited, so that the surveying of line routes has been on a more comprehensive basis than is usual. At first, it was thought that the extensive use of aircraft would be required to survey the ground and set out the lines. It was found, however, that the relatively level terrain, except near the Zambesi, and the reasonably open nature of the bush, enabled the work to proceed on fairly orthodox lines. Aircraft were used only to facilitate the initial selection of routes in the more inaccessible districts.

The servitudes (or wayleaves) for single and twin lines are specified as 260 and 440 ft wide, respectively, but as a result of the survey it has been possible to reduce them by about 20% in some places. For much of the distance it has been necessary to clear the bush from undeveloped land. Straight sections of up to 70 miles have been set out. Bulldozer clearance has been preferred to lopping and felling as it is quicker and removes the stumps, thus easing the problem of controlling subsequent growth. The anthills, which occur mostly in Northern Rhodesia, have to be demolished by undercutting and levelling by bulldozer.

(7) FUTURE DEVELOPMENT

The time from ordering the first equipment in 1956 to the commissioning of the last generator at Kariba about 1971 is long enough to make any further planning highly conjectural. Nevertheless in designing an entirely new system of such magnitude it is necessary to take account of probable future trends, and to make as much allowance for them as possible without incurring speculative costs.

(7.1) Growth of Load and Generation

There is every expectation that the demand in Rhodesia will continue to grow, and consideration is already being given to future power sources. Present estimates, which may well prove conservative, suggest a demand of about 3 500 MW by 1980.

Kariba itself may be rearranged to give greater output than the 1 200 MW at present planned if lower load-factor operation is found justified by further studies. Another possible source is the Kafue scheme, where perhaps 1 000 MW could be made available, and there is a site having a potential of about 1 000 MW at the Cohora Bassa Gorge in Mozambique about 300 miles down stream from Kariba. Other possible sites for hydroelectric schemes of smaller capacity exist at several places in the Federation, e.g. the Shire River scheme in Nyasaland. Pithead generation in the Wankie coalfield cannot be ruled out, and the possibility of nuclear power production in the future must not be neglected. The influence of some of these possibilities on transmission development could be profound.

(7.2) System Extensions

The addition of switching stations at Broken Hill and Sinoia in the later stages of present planning has already been discussed. These points make natural centres for the development of supplies at a lower voltage. Other centres for such development may be made by tapping the 330 kV system. If Kafue is built the northbound lines from Kariba will be turned into Kafue switchyard.

As the system develops it may well prove economic to increase its capacity by measures other than the addition of parallel circuits, e.g. series capacitors could be used in both northern and southern routes. It may be thought advisable to make an experimental installation of this type in advance of system requirements.

Further developments are more difficult to predict. It seems likely that additional supplies in the south will be provided at a lower voltage for some time, but 330 kV extensions may eventually be needed to provide new points of bulk supply. In the copper belt, developments of the 220 kV link with the Belgian Congo are expected to be used to reinforce the 66 kV network.

(8) ACKNOWLEDGMENTS

The authors wish to express their thanks to the Federal Power Board and Messrs. Merz and McLellan for permission to publish

the paper, and to their many colleagues whose work has contributed so much to the design of the system and the preparation of the paper.

(9) REFERENCES

(1) 'Survey of Rhodesia and Nyasaland', *Financial Times*, 21st October, 1957.

(2) INTER-TERRITORIAL HYDRO-ELECTRIC POWER COMMISSION: 'Report on Kariba Gorge and Kafue River Hydro-Electric Projects', Central African Council, Salisbury, S.R., May, 1951.

(3) FRENCH MISSION: 'Report on the Kariba Gorge Hydro-Electric Project', Paris, October, 1954.

(4) FRENCH MISSION: 'Report on the Kafue Gorge Hydro-Electric Project', Paris, October, 1954.

(5) COYNE, A.: 'Kariba Gorge and Kafue Gorge Hydro-Electric Projects', Paris, November–December, 1954.

(6) GIBB, SIR ALEXANDER, AND PARTNERS: 'The Kariba Hydro-Electric Scheme', *Water Power*, 1958, **10**, pp. 4 and 44.

(7) ENGSRÖM, R., and LENGSTAM, S.: 'Field Tests show Single-Phase High-Speed Reclosure justifiable at Higher Voltages', *Electric Light and Power*', 25th March, 1957, p. 135.

(8) ROKOTYAN, S. S., and LEBEDEV, B. P.: '400 kV Transmission Systems in the Soviet Union', *Proceedings I.E.E.*, Paper No. 2400 S, December, 1957 (**104 A**, p. 471).

(9) SCHAER, F., and BALTENSPERGER, P.: 'Short-Circuit Tests with Rapid Reclosing on the 220 kV Mettler–Lavorgo Line', *Power Apparatus and Systems*, December, 1956, p. 1137.

(10) MORTLOCK, J. R., and HUMPHREYS, C. F.: Discussion of 'System Stability Load and Frequency Control', Group 32, C.I.G.R.É., Paris, 1956, **1**, p. 627.

(11) BROOKS, C. E. P.: 'Climate in Everyday Life' (Ernest Benn, 1950).

(12) BEWLEY, L. V.: 'Protection of Transmission Lines against Lightning: Theory and Calculations', *General Electric Review*, April–May, 1937.

(13) ANDERSON, R. B., and JENNER, R. D.: 'Lightning Investigations on an 88 kV Transmission Line in Southern Rhodesia', *Transactions of the South African I.E.E.*, Part I, August, 1948, p. 217, and Part II, September, 1948, p. 257.

(14) ANDERSON, R. B., and JENNER, R. D.: 'A Summary of 8 Years of Lightning Investigation in Southern Rhodesia', *ibid.*, Part I, July, 1954, p. 215, Part II, September, 1954, p. 261.

DISCUSSION BEFORE THE NORTH-EASTERN CENTRE AT NEWCASTLE UPON TYNE, 24TH MARCH, 1958

Mr. P. E. Gaze: The authors stress the necessity for economy of space at Kariba 330 kV switching station. The original substation layout was designed to accommodate any type of circuit-breaker. In the final layout it has proved possible to reduce the bay centres from 70 to 60 ft by the use of vertical-lift isolators, while it has also proved possible to reduce the bay depth from 175 to 154 ft, half by the use of bulk-oil circuit-breakers accommodating the current transformers in the bushings and the remainder by detailed attention to layout, at the expense of increased height.

The conductor used throughout the substations comprises 127 solid strands of pure aluminium. The connection fittings are of cast aluminium and are pressed on to the conductor by portable power-operated hydraulic tools.

The vertical-lift-type isolators employ pressure-line contacts at both ends of the isolator blade. The hinged drive is so arranged that, when the blade has been fully lowered, it then turns through 45° to engage spring-loaded contact fingers. The operating mechanism is motor driven through a friction clutch; the isolator being opened or closed in approximately 10 sec.

The 330 kV circuit-breakers, of the lenticular bulk-oil type, have six main breaks per phase, each arc interruptor being shunted by its own wire-wound switching resistor. By utilizing a special form of insulated crossbar, the three breaks on each side of the breaker are connected electrically in series while operating mechanically in parallel.

The arc interruptors are of the side-vented pattern, embodying contactor-type contacts. Each switching resistor is wound non-inductively in one continuous length of nickel-chrome wire. The insulation of the crossbar and of the main lifting rod and guides is of tropical-grade resin-bonded laminated wood.

The breaker is pneumatically closed and spring opened, torsion-bar-type accelerating springs being employed.

The combination of resistance switching and high mechanical speed which has been employed reduces to a low level the over-voltages produced when switching capacitance or low inductive currents.

Tests carried out at the Fontenay testing station of Électricité de France, on a 4-break resistance-switched 220 kV oil circuit-breaker which is otherwise similar in design to the units under discussion, gave maximum over-voltages below twice the peak leg voltage. The tests included the switching of magnetizing currents up to 100 amp; these being achieved by loading power transformers with reactors. The tests also demonstrated that 100 amp was above the critical value for the interruption of low inductive currents. The tests included opening 220 kV lines of some 600 km in length, the capacitive currents being approximately 300 amp.

Based on these tests it is not unreasonable to expect that, with the 6-break breaker being employed, the over-voltages produced under the switching conditions on the Kariba scheme will be appreciably below the 600 kV mentioned by the authors.

The scheme described by the authors for preventing line circuit-breakers from opening unless the two ends of the line are reasonably in phase is interesting. I would, however, like to make it quite clear that the circuit-breakers being installed are quite capable of operating satisfactorily on the system without this easement.

It is intended to test these breakers to prove their ability to interrupt fault currents up to 25% of the maximum breaking capacity with a recovery voltage equal to full phase opposition. This is becoming increasingly common practice with makers of British circuit-breakers.

Mr. S. E. Newman: It is interesting that, as stated in Section 3.2, the development of the system was found to be largely controlled by the transient stability, although this is perhaps to be expected in view of the long transmission distances. On the other hand, the reference in Section 5.1.3 to dynamic margins in connection with under-excited operation of the generators would apply to steady-state stability. Is the automatic voltage regulation an essential requirement for either transient or steady-state stability, or does it, in effect, provide the desirable safety margins?

The results of the proposed single-pole auto-reclosing field tests will be both interesting and valuable, as such information is very limited. It appears that no auto-reclosing is to be provided

on the Norton–Salisbury spur. Will the second line be provided in the first instance as shown in Fig. 4 rather than at a later date as indicated in Fig. 2? Occasionally 2-pole auto-reclosing has been suggested to cover line-to-line and double line-to-earth faults. I assume that such a possibility was not considered for the Kariba system, as it would appear of very doubtful value.

At Kariba power station the surge diverters will be underground with the transformers rather than above ground as at the Swedish 380 kV Harspränget power station and on the Australian Snowy Mountains scheme. With the surge diverters underground the best possible protection is given to the transformers, but the above ground cable ends appear rather more vulnerable.

In Fig. 5, could the authors confirm that it will not be necessary to have more than two generators in operation when requiring the reactors in circuit. If this is not the case, difficulties might arise with voltage-regulator compensation.

Lightning protection is provided by masts. Has the protective space been based on a straight-sided, or concave-shaped, cone having a radius of base equal to the height of the mast?

In Section 5.2.2, the rates of rise of restriking voltage, particularly at 100%, appear to be high, bearing in mind the number of transmission lines radiating from Kariba. The probability of a fault on one line with none other connected to the 330 kV busbars is very small. Could the authors state the conditions on which these rates of rise are based?

The characteristics of the transmission-line insulators are given in Table 4. The values, including corona voltage for the station post insulators, would be useful.

Mr. K. Austin: My first comment concerns the relative merits of the use of copper as opposed to steel-cored aluminium for the overhead conductors. Bearing in mind the decline in the cost of copper, and considering not only the question of first cost but also factors such as possible longer life of copper and the desirability of aiding the local copper industry, I would ask whether now the same decision would have been made to use s.c.a. conductors.

With regard to conductor spacers, I would question the reasons why the flexible-ring-type spacers were considered to be the most suitable, and, in particular, why they were preferred to the type normally employed in this country.

In the design of the intermediate towers, was consideration given to the possibility of using laminated timber or glass fibre for the cross-arm members?

My next comments concern the foundation design, which is perhaps the most uncertain aspect in the structural design of overhead lines, for whilst towers, conductors and insulators can have their designs proved by tests, this is not practical for foundations, where strength would vary from one tower position to another, and would even change with weather conditions. Practical reasons dictate that standard types of footings should be used as far as possible, and that prior soil investigation be kept within reasonable limits. However, in Rhodesia there is the danger that standard footings installed during the dry season in apparently good soil conditions, may be inadequate in the wet season when the site may well resemble a swamp. Therefore, with this in mind, I wonder whether soil investigations of a far more extensive nature than is normal would have been justified.

Finally, I wonder whether the authors could add further data on the basic design of the foundations against the shear, uplift and thrust loads?

[The authors' reply to the above discussion will be found on page 602.]

DISCUSSION BEFORE THE SUPPLY SECTION, 30TH APRIL, 1958

Mr. F. J. Lane: The establishment of a new transmission system is an important event, particularly when it can be planned as this one, without being seriously committed by existing arrangements. Two questions are vital: what is the system intended to do, and what is the right voltage to select?

The answer to the first question does not seem to be clearly defined. The authors speak of the system as an 'integrated' one, but this implies operation of all the connected plant in such a way as to deliver the energy to the consumer at the least cost at all times of day and season. There is no evidence in the paper that the implications of interconnected operation were examined technically and economically in relation to the design of the system.

The choice of voltage is crucial. The authors are to be congratulated on their thorough examination of the different possibilities in a somewhat restricted time; but while realizing that the final decision was determined by the immediate availability of capital, I am disappointed that 330 kV, a standard voltage but not a 'preferred' standard, was selected.

A new system such as the present one provides not merely a number of load delivery points, but a basis on which the electricity in the area can be developed in the future. A decision on the size and location of new generating plant represents a serious capital commitment but is localized and individual in its technical outcome, whereas, for the transmission system, the decision will affect future planning of supplies and, unless one is careful, may well commit the next generation of engineers to continued use of unnecessarily specialized or outdated equipment. It is all too easy to restrict or defer capital outlay for this part of the system and then to fret at the restrictions on economic operation which must follow as a result four or five years later.

The conflict between immediate capital outlay and preparation for the future is most pointed at the outset of a new system or a change of voltage and is very evident in the paper. Could not 380 kV costs have been shown in Fig. 3 in order to make a direct comparison? Could not some economic comparison have been presented, taking into account transmission losses, maintenance costs, etc., such as has been presented in similar papers elsewhere?

Under the heading of security of supply, single circuits are considered to be reasonable connections, subject to suitable provision for stability, high-speed reclosure and lightning protection. The limitations imposed by the single-circuit connection are more likely to be evident in the outage times necessary for routine maintenance and inspection, bearing in mind that the distance from Kariba to Kitwe is 287 miles, for the correction of construction and erection errors, for replacement of damaged insulators or conductors and, later, for constructional modifications at new points of supply.

When the paper discusses intermediate switching stations, I would have expected some mention of the possibilities and economics of series capacitors as a means of reducing the effective line impedance. There is a reference to series capacitors in Section 7.2, but this is only to the advisability of an experimental installation of capacitors. This is a surprisingly tentative approach to what, in suitable circumstances, is a well-proved transmission component.

An underground rock-hewn power station inevitably presents problems in earthing the structures, frames and tanks. What arrangements are being adopted at Kariba?

Parallelism with telephone circuits and radio interference are not mentioned. Do these present problems of any magnitude?

I congratulate the authors on a design well considered and wish them the best of luck as it goes forward to completion.

Signor F. Bianchi di Castelbianco (*Italy*): It will be agreed that there is nothing very special about this work of erection. So far we have not encountered any unexpected difficulty. The job is running very smoothly and it should be completed on time and be satisfactory.

The design of the towers which was adopted was found to be the most economical. The advantage of the world-wide competition which preceded the award of the contract is that it brings out the real economics of design. It is all very well for different people to suggest that a special design of their own is more economical than some other design, or is even the most economical of all designs, but it is another matter to see that design stand up under the critical conditions which govern tenders for works such as the Kariba project. This should be borne in mind when different sources claim to have revolutionary tower designs.

The paper refers to the longitudinal strength of the suspension towers, which is now possibly the ruling factor in the economics of transmission tower design. In some modern lines, we find that the designers go even further and actually renounce every longitudinal strength. On the whole, however, the provision of a little longitudinal strength in the suspension towers does not make the design much more expensive. This capital is well invested in ensuring the success of transmission lines of this kind.

Mr. W. Casson: I should have thought that 3-phase reclosure would have been more suitable for the Kariba scheme, taking all the factors into consideration, particularly in the mesh-connected section south of Kariba where there are circuits in parallel. Three-phase reclosure allows smaller limits of de-ionizing time to be obtained to ensure extinction of the fault arc. However, I can see that the effect of switching in a long circuit on three phases as against two or one is a factor which has to be considered, and that may be the reason for deciding on single-phase reclosure.

Voltage regulation is obviously a great problem. From Section 4.1, it appears that transmission in the first stage is slightly below the surge-impedance loading of the line, and therefore only a small amount of reactive-power compensation is required. If this is so, would it not have been more economic to have installed a certain number of synchronous condensers initially with, say, 50% under-excited and 100% over-excited regulation, bearing in mind that they are required in the second stage and will replace shunt reactors?

In their very comprehensive control scheme, have the authors considered providing metering equipment for indicating incremental reactive-power demand with voltage variations on the system to assist in controlling from Kariba the voltage regulation at the ends of the very long feeders?

From the consideration of system stability, the generators had to be specially designed. However, Figs. 6(*a*) and 6(*b*) indicate that the full rating of the generators will be attained much before the stability margin is reached. This margin would be further increased if the action of the high-speed voltage regulators were taken into account, as stated by the authors. I should therefore like to know the reasons for going to the greater expense of a design of generators with such a high short-circuit ratio. Perhaps the extra cost, which may be some 20% on the generators, could have been better spent on series capacitors.

In view of the statement made in Section 5.2.1 drawing attention to the serious disturbance that would follow a fault at Kariba, I shall be glad to know whether busbar protection has been considered for that station.

I was very interested to see that provision is being made for instruments to measure residual voltage and residual current at the end of each circuit to enable the point of fault to be calculated. This method has been used successfully by Électricité de France for many years on their 225kV system. I observe that the instruments are to be calibrated on site and shall be glad to know what this really means and also whether the high residual capacitance current is likely to affect the accuracy of measurements to any extent.

In view of the recent decision to provide a tapping point at Lusaka and the installation of a line circuit-breaker, I shall be glad to know whether it is proposed to tap the transformer or transformers supplying Lusaka direct off the line, and, if so, what type of intertripping, if any, would be provided.

Dr. J. R. Mortlock: For transient-stability studies we have not found it feasible to use a time shorter than the 0·125sec. We also use double-line-to-earth faults, and to that extent we agree with the authors.

For single-pole reclosing, we carried out a number of tests to establish what the parameters were generally. They may be of interest.

Fig. A (i) shows the data required for each system operating condition. Having obtained them, we can then use the circuit

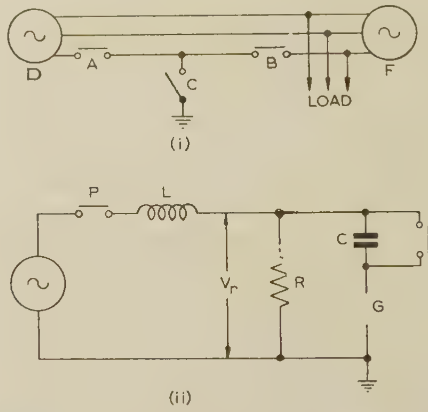


Fig. A.—Derivation of test circuit for single-phase reclosing.

(i) Basic system
For each value of D, F and load, we have to find

I_f = Fault current; A, B and C closed.
I_r = Residual current; A and B open, C closed.
V_r = Residual voltage; A, B and C open.
V_{rt} = Residual restriking voltage across C with A and B open.

(ii) Test circuit

I_f: P, Q closed, G closed with fine wire.
I_r: Q opened after 4–20 cycles.
V_{rt} Approximated by damping test circuit: with resistor R.
Circuit finally cleared by opening P.

shown in Fig. A (ii) and reproduce the conditions that would occur across the fault gap. The major advantage of the lower circuit is that it is necessary to work at the voltage V_r, which is a fraction of the main voltage. As will be seen later, it is about 30kV.

Using the technique in Fig. A, with a moderate wind, there was only one failure in something like 20 tests (see Fig. B), whereas with a longer gap inside a building, so that the wind is ineffective, there are practically all failures. Therefore, the first variable to eliminate was any effect of wind.

The purpose of the next series of tests (see Fig. C) was to determine the effect of fault current. At 700 amp there were more or less consistent failures. If the current is increased there is success. It is not always fully appreciated that the fault current can have a major effect on success or failure. It means

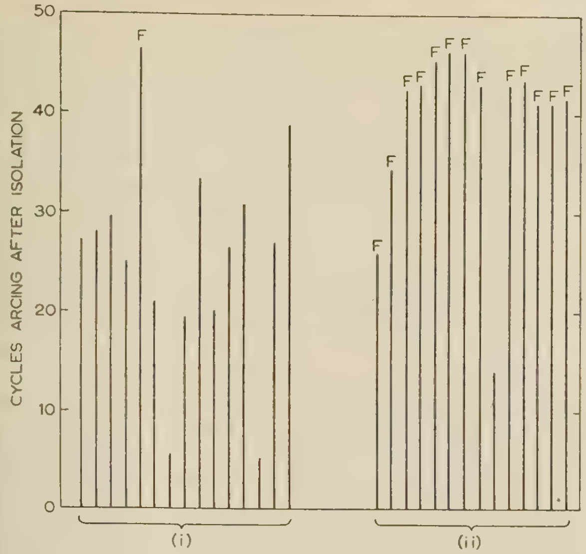


Fig. B.—Effect of wind on arc duration: 330 kV, 275 miles.

	Wind	Fault current	Fault duration	Residual current	Residual voltage	Gap length
		amp	cycles	amp	kV	in
(i)	Moderate	740	4	48	29	96
(ii)	Nil	700	5	48	29	120

F. Cleared by station circuit-breaker.

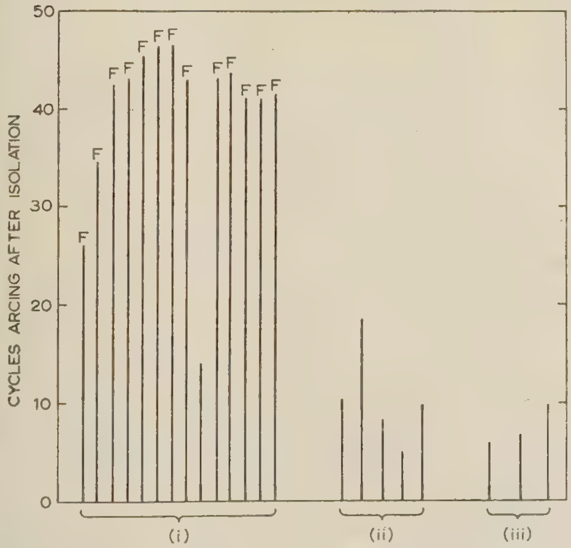


Fig. C.—Effect of fault current on arc duration: 330 kV, 275 miles.

	Wind	Fault current	Fault duration	Residual current	Residual voltage	Gap length
		amp	cycles	amp	kV	in
(i)	Nil	700	5	48	29	120
(ii)	Nil	1 300	5	39	20	120
(iii)	Nil	1 500, 1 700, 1 800	10	40	23, 25, 27	120

F. Cleared by station circuit-breaker.

that it may be necessary to run excess plant to ensure that there is sufficient fault current.

With everything constant, the fault duration is increased (see Fig. D). The fault current was small in this case, but the duration had no significant effect.

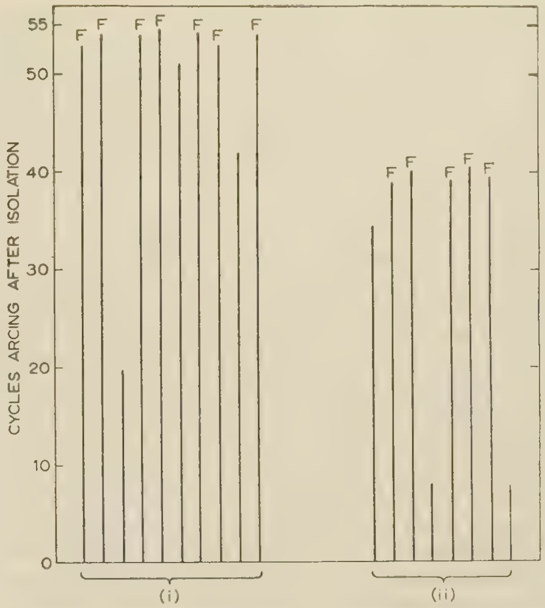


Fig. D.—Effect of fault duration on arc duration: 330 kV, 100 miles.

	Wind	Fault current	Fault duration	Residual current	Residual voltage	Gap length
		amp	cycles	amp	kV	in
(i)	Nil	270	7	24	27	120
(ii)	Nil	270	20	24	27	120

F. Cleared by station circuit-breaker.

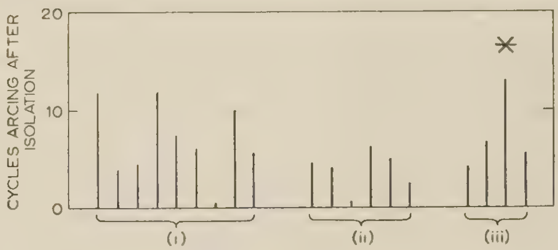


Fig. E.—Effect of fault duration and fault current on arc duration: 330 kV, 100 miles.

	Wind	Fault current	Fault duration	Residual current	Residual voltage	Gap length
		amp	cycles	amp	kV	in
(i)	Nil	2 250	7–8	24	24·5	120
(ii)	Nil	2 200	20	24	22·8	120
(iii)	Nil	2 660	20	32	29	120

* Approximately 400 kV system.

Fig. E refers to the Snowy Mountains scheme. With sufficient fault current available, fault time does not seem to have any major effect.

Another factor to which the authors refer is the possibility of 'losing' Kariba. We recently had experience on a 325-mile line. The arrangements were made so that, if the voltage could not be held and became excessive and if the synchronous-condenser excitation went to its minimum, circuits would be dropped to relieve the condition. System tests proved effective. Are the authors taking any precautions to do the same thing?

I understand that in the Copper Belt, which is mainly a mining area, frequency relays are used to preselect circuits so that, if the tie is lost and the local generation cannot meet the

load, essential supplies are maintained. Can the authors give the background to any experience in running for two or three years under these conditions in the Copper Belt?

Mr. P. J. Ryle: This project is close to a great copper-producing centre, and it has been asked whether copper line conductors were seriously considered. Steel-tower line costs depend on many factors apart from the actual conductor cost. However, for lines at and below, say, 88 kV, where the overall conductor diameter is electrically immaterial, it can be stated, very roughly, that overall copper line costs would at present be competitive with corresponding s.c.a. line costs only if the price of copper were in the region of £120–130 per ton. The present price is £170–180 per ton. For very-high-voltage lines, considerations of corona and radio interference set a lower limit to conductor overall diameter. The Kariba s.c.a. conductors are approximately 1 in diameter, with an equivalent copper cross-section of $0\cdot35\,in^2$. If made of copper they would still have to be approximately 1 in diameter, and, if normally stranded, would have a cross-section of about $0\cdot67\,in^2$, at absolutely prohibitive cost. For copper, therefore, the only thinkable approach would be hollow conductors; these have been used (not entirely satisfactorily) in the United States and Germany and are not now considered commercially practicable. There are mechanical lower limits to wall thickness of hollow conductors, and, for the Kariba lines, I estimate that, for hollow copper conductors to be competitive with steel-cored aluminium the price of copper would not have to exceed about £100 per ton. As stated above it is now about £170–180 per ton, at which price the total *extra* cost on the present project (about 900 route miles, 3-phase, twin conductors) if hollow copper conductors had been used would approach £1 000 000. Further explanation is needless, but this subject may be rounded off by a reminder that, at the initiation of the work, the price of copper was actually over £300 per ton.

An impression has circulated that the Italian tower designs are lighter than those offered by British tenderers. This is incorrect; the British tender designs were about 4% lighter than the Italian, but the price per ton of Italian steel, delivered, was disproportionately low.

The relative distribution of main transmission system costs is always interesting. Ignoring generation, I should like to know the approximate percentages of total cost represented by (*a*) switching stations excluding transformers, (*b*) transformers, and (*c*) transmission lines.

Mr. M. V. Ratcliffe: Many of the problems of system design which the authors must have had to tackle cannot be solved entirely with a slide rule, or, indeed, by the use of any other form of computer. All these equipments have to be fed with the facts, and, in practice, some of the facts cannot be expressed in figures. Other data, like the forward load estimates, assumed future rates of interest, etc., are so liable to variation by alteration in conditions of world economics that one has to fall back on engineering judgment, and it is probably just that kind of judgment which the consulting engineer is able to supply.

The authors' decision to rely on single-circuit supplies in the early days is an example of this. While it may be possible to estimate the probable outages to be expected, and from that to estimate the resulting loss in revenue, I do not think that anyone can evaluate the possible loss of goodwill and the effect on the growth of future load which may result from total shutdowns.

So far as I can see, the main load centres all have existing generating plant, and from the few figures given it appears that, during a period when single-circuit supplies are relied upon, this existing plant could take over some two-thirds of the load in the event of a long shut-down due to fault or damage or maintenance. Nevertheless, the decision is a bold one, and future experience will be of great interest.

The authors may be criticized because the voltage of 330 kV which has been selected is not among those which the I.E.C. is seeking to establish as a standard. On a scheme like this the biggest single item affecting the overall economics is the expenditure on overhead lines. The loading of such lines is governed by questions of stability or voltage regulation, and for both these factors the transmission capacity is proportional to the square of the voltage. Thus the step between 275 and 380 kV just about doubles the transmission capacity of a single line. In my view, this step is too great, and the use of an intermediate voltage is fully justified if it results in a substantial reduction in capital cost.

I would have expected air-blast circuit-breakers to show some advantage where single-phase auto-reclosure is being used. I would be interested to know whether the choice of bulk-oil circuit-breakers was made as a basic decision and, if so, what technical reasons the authors had in mind.

I think that the authors were quite right in choosing single-circuit lines for a country with such a high lightning level as that obtaining in Rhodesia. I am quite sure that two single-circuit lines running at something like 150 yd separation have an enormously increased security factor as compared with double-circuit lines.

There have been one or two suggestions that the system ought to have been designed taking series capacitors into account. I feel that the authors are quite right to leave them out in the first instance. They are good to have in reserve for future load expansion.

Mr. F. W. Gee: My excuse in confining my remarks to transformers is that I do not think it would be fair to judge their importance in the scheme by their very low proportion of the total cost. Some of the comments which have been made are not exactly on what the authors have said but on the little hints they have given which hide so much.

They refer in Section 2.5 to a 3 ft 6 in railway gauge, with a very small weight per axle, and to special road vehicles. This does not emphasize the work carried out by the authors in co-ordinating the varying requirements of different manufacturers.

There is another aspect in which just one small remark stirs our imagination as to what is hidden behind it. After reference to various decisions taken although the evidence in favour 'is far from conclusive', there is the simple statement in Section 3.3.1 that field tests will be conducted and that the results obtained in service will be of great interest. I regard that as a triumph of understatement. I should say that we and the authors are eagerly awaiting these results.

Mr. P. M. Hollingsworth: The 330 kV cable circuits in the Kariba transmission scheme which will run from the power station to the overhead-line terminal have several features of interest. First, the cable itself is of considerable size. It is a modified type of oil-filled cable with $0\cdot85\,in^2$ hollow conductor and insulation thickness of $1\cdot1$ in, giving an overall diameter of just under 5 in. From the point of view of manufacture, a major operation is the application of the insulation, the dimensions of which are somewhat outside the usual run of experience, especially as it has to conform to the stringent standards of uniformity and performance laid down by the authors.

We are told that the Kariba plateau is one of the worst lightning areas in the world and also that the cable is expected to contribute to the protection of the transformers. The $1\cdot5$ MV level which the authors have laid down means, in the design sense, aiming at breakdown figures of the order of $1\cdot7$ MV.

Probably the most exacting requirement of the cable installation is provided by the route itself. There are nine cables in

three circuits, together with a spare. The cable traverses a horizontal tunnel for about 240 ft until it reaches a vertical 550 ft shaft. Between the shaft and the overhead line, a distance of approximately 700 ft, the cable is laid direct in steeply rising ground, bringing the total head to about 600 ft. This is equivalent to an oil pressure at the bottom of 250–300 lb/in^2, and the cable sheath is reinforced for that pressure.

In the shaft, the cleating arrangements have to be such as to hold the cable without creep. The weight is about 70 lb/yd, totalling some 22 tons for each cable. At the same time the cleats must allow for movement in each span due to expansion under load.

The porcelain terminal insulators situated at the bottom of the shaft in the power station are also subjected to the full oil pressure. They are of single-skin design, associated with condenser-cone stress control which enables the diameter of the porcelain to be kept to a minimum. This is an important factor in consideration of the high internal pressure conditions.

The authors have stipulated that the condenser-cone assembly shall be so constructed as to be capable of retaining the full pressure without significant leakage should the porcelain fail or be damaged.

The installation of the cables will be facilitated by the fact that they require no joints. This means that they will be manufactured, shipped and handled on site in 700 yd lengths, involving a gross weight per drum of about 30 tons.

Mr. C. F. Humphreys: Difficult terrain is often encountered at sites for hydro-electric stations, and according to the authors, Kariba is no exception. Owing to the high cost of preparing such sites, it is essential that the substation layouts be kept as compact as possible. Reductions in both the length and the breadth of the site have been found possible by using bulk-oil circuit-breakers of the lenticular type, combined with vertical-lift isolators.

With this type of circuit-breaker, overlapping protection, which is becoming increasingly important with increasing voltage, is obtained using bushing transformers, thus avoiding the additional space taken up by separately-mounted current transformers. The use of the vertical-lift isolator raises the height of the overhead structures by some 5%, but the combination of circuit-breaker and isolator reduces the floor area of a typical bay by some 20%.

The conductor used for the busbars and connections is of interest. At this voltage corona considerations dictate the size and the arrangement of the conductors. Bundle conductors have been used, but after careful consideration it was decided that the multiplicity of joints, the complications during erection and possible difficulties under short-circuit conditions, made such a scheme undesirable at the substations. A single conductor is technically preferable, but, considering the voltage and altitude, such a conductor must have a minimum diameter of $2\frac{1}{8}$ in. An aluminium conductor of approximately this diameter and having the required current rating was available consisting of 127 strands of 0·169 in-diameter pure aluminium wire, giving an overall diameter of $2\frac{3}{16}$ in.

From experience available in this country on the 275 kV Grid system, a bundle conductor using copper and having a similar performance electrically would comprise two $1\frac{1}{8}$ in Holten conductors, but the additional clamps, spacers, etc., necessitated by this arrangement would increase the weight by some 50%. The cost of the steel structures is dependent upon the height of the structure and also upon the tension of the strained connections. The reduction in the pull on the structures brought about by the use of aluminium conductor more than compensated for the additional height imposed by the vertical-lift isolators.

The well-known difficulty of jointing aluminium caused by its high-resistance oxide film is overcome by the use of a very compact compression joint using an electrically-operated hydraulic press of some 100 tons. The pressure developed is sufficient to force the wires into intimate contact with each other and with the connector and to break down the oxide film.

Heat-run tests and millivoltage drop tests show that the efficiency of the joint is at least as good as the equivalent length of the conductor.

Mr. J. F. Bird: Section 2.4 deals briefly with the climate. The remarks are devoted entirely to water, and recent experience on site has shown that this has not been entirely without justification. There is, however, at least one other factor associated with climate which cannot be neglected, and that is temperature.

Although most of Rhodesia enjoys fairly reasonable temperatures, which hardly ever rise above 95° F, conditions are not quite the same at Kariba, and during the recent hot season, temperatures of 120° F in the shade have been experienced. These may be related to temperatures of something like 150° F in the sun. This, in turn, has a bearing on the equipment, which will have to stand out in the sun.

In particular, the switchgear, which is of the bulk-oil type, requires access to the tank for maintenance purposes. From time to time an unfortunate maintenance engineer will have to climb inside a very hot, oily and uncomfortable tank and I wonder whether any thought has been given to his difficulties.

Mr. M. F. Bedil: My interest is confined to the 80 MVA generator transformers. The authors mention that the size of the total installation was fixed by transport considerations. It would be interesting to know which part of the equipment was the limiting factor so far as the size of the power station is concerned, because the generator transformers form one of the rather heavy items of equipment.

The generator transformer which I have in mind is not as heavy as that mentioned by the authors, who gave a weight of 98 tons as against mine of 92 tons. From studies which have been made in the preliminary stages, we have come to the conclusion that transformers up to 100 MVA could be transported within a given limit of 102 tons and within the given railway gauge. Should it be possible further to increase the flux density to a still acceptable value, or by means of some detachable external part of the transformer, it might even be possible to increase the size to 120 MVA.

Mr. R. G. W. Smith (*Australia*): The paper impresses me with the similarity between the considerations which led to 330 kV being chosen as the voltage both for the Kariba scheme and the Snowy Mountains scheme in Australia. It appears that, in both cases, 330 kV gives the most economical number of transmission lines, and 275 or 380 kV would have led either to a surplus transmission-line capacity under normal conditions, or a scarcity when one line is out.

It is noted that the conductor size and arrangement is the same, and also that single-phase reclosure is essential during the early stage of development when one line only is in service. I note from Dr. Mortlock's contribution that deionization in 15 cycles is doubtful, particularly with small fault currents. I am looking forward to field tests which are scheduled for this time next year.

Earthing difficulties are also present in the Snowy Mountains area, where earth resistivities of up to 10 kilohms-ft are encountered. We are concerned with contact voltages and earth potentials affecting communication circuits, etc. In the underground power station T1, where the 330 kV neutrals are earthed, we are not providing separate earth electrodes but bond reinforcing and other metalwork, and we use this as the main earth. In addition, this forms a Faraday cage, minimizing contact potentials within the power station during times of system fault.

I would like to know what contact voltages the authors expect at Kariba.

It is noted that the 330 kV cable at Kariba is $0\cdot85\,\text{in}^2$ cross-section, giving a current density of about 500 amp/in^2. I would be interested to know why such a low current density is used. The Snowy Mountains scheme uses $0\cdot325\,\text{in}^2$ cable, which gives a current density of about 850 amp/in^2.

It is noted that a 2·2 in-diameter conductor is used for switching-station busbars; it is stated that this size was chosen with corona inhibition in view. We are using 1·77 in-diameter conductors, at 5 000 ft altitude for busbars, and also for transmission lines in high-altitude locations where icing is expected. I should be interested to know whether the authors think that we will have corona trouble with the smaller-diameter conductor.

For line protection we propose both carrier-accelerated distance protection and carrier-current phase comparison; both with phase selectors for single-phase reclosing. We are having some difficulty in obtaining carrier equipment with sufficient power output to deliver a definite signal over 90 miles of 330 kV line, especially during rain or fault condition. It is understood that the designed low-power output is caused by regulations in this country. I should be interested to know how the authors have overcome this problem with the longer Kariba lines.

Mr. C. C. Barnes: My remarks are confined to cables, and I share Mr. Hollingsworth's regret at the scanty treatment given to this important item of equipment.

Why have the authors chosen an oil-filled cable? With a total head of the order of 600 ft, a good case could be made for a gas-filled cable. It would be very interesting to know the relative technical and economic merits of these two types of cable for the scheme in question.

My next point concerns the 1·5 MV impulse test. That is a very severe level indeed. Will that test be made hot after the manner normally required now by the Central Electricity Generating Board, and what is the maximum conductor temperature for the cable?

Why has a maximum stress of 110 kV/cm been accepted? For 275 kV service, cable makers are willing to offer cables designed for 130 kV/cm. It would be interesting to have the authors' views on the limit of maximum stress which they are prepared to accept. It may be that the very onerous impulse test sets a level for this requirement.

As Mr. Smith mentioned, the current rating seems very low indeed, and it would be helpful to know the basis used for computing the conductor size.

Mr. A. R. Parish (*communicated*): The authors are to be congratulated on their use of aluminium substation conductors, and it would be most useful if they would indicate the methods of avoiding corrosion where connection is made to copper items. The supposed difficulty of making such joints satisfactory in service is undoubtedly holding up the greater use of aluminium in outdoor substations and experience on this project will be invaluable.

The authors mention Kariba as being one of the worst lightning areas in the world. However, isoceraunic levels of 90 are reported from Florida, where the extreme lightning precautions mentioned by the authors are not commonly used. Are the conditions at Kariba so much worse, and is there not some evidence that high isoceraunic levels in the tropics are caused by cloud-to-cloud rather than cloud-to-earth discharges?

It would be interesting if the authors would indicate the method they have used to determine the limit of the protected area, as shown in Fig. 7. This does not appear to be based on the conventional approaches, since extension of straight portions of the boundary do not pass through the positions of the towers. In the case of the substation shown in Fig. 8, the protection on the same basis as that in Fig. 7 would appear to leave large parts of the busbar run unprotected.

Mr. N. G. Simpson (*communicated*): Freedom from ice loading removes the principal line structural design hazard, but the effects of high transient over-voltages remain an electrical uncertainty.

Line insulation is governed by switching surges, which incidentally provide acceptable lightning outage rates assuming 20-ohm footing resistances. A small insulation increase offers little advantage, since, even with 25 ohms, a one-third increase is necessary for an equivalent outage rate. The 20-ohm resistance level is therefore a critical factor.

Analysing line mechanical loadings, the gust velocity for an ultimate wind pressure of $37\cdot5\,\text{lb/ft}^2$ $(15 \times 2\cdot5)$ is about 85 m.p.h., presumably based on available records, but this seems low. Investigations on conductors in Great Britain and elsewhere show gust fronts on large span lengths to be of limited length. This factor has been used in Sweden to reduce statutory conductor wind pressures by a factor of 0·65 on the equivalent velocity on spans exceeding 1 000 ft. On this premise the Kariba conductor wind pressure could be $9 \times 2\cdot5 \times 0\cdot65^2 = 9\cdot4\,\text{lb/ft}^2$ (ultimate) or $3\cdot75\,\text{lb/ft}^2$ working, which is admittedly too small. Suppose, however, that a maximum velocity of 106 m.p.h. is considered (New British draft Regulations for Overhead Lines). The equivalent conductor wind pressure is $36\,\text{lb/ft}^2$, reducing to $15\,\text{lb/ft}^2$ (ultimate) with the wind-front factor and to $6\,\text{lb/ft}^2$ $(15/2\cdot5)$ working pressure, which may be compared with the Kariba pressure of $9\,\text{lb/ft}^2$. This shows an available margin on a limited wind-front basis. As there is no ice, other structural uncertainties are substantially reduced, so that altogether there is some justification for a so-called factor of safety of less than 2·5 on structures, excluding foundations.

Savings could have been utilized in giving more flexibility to the earth-footing resistance problem through greater insulation and clearance and possible scope for a future voltage increase to 380 kV.

THE AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Messrs. F. C. Winfield, T. W. Wilcox, and G. Lyon (*in reply*): In order to keep the reply short, no comments are made on points raised in the discussion with which we are in substantial agreement, and the replies are grouped under the appropriate Sections of the paper.

Governing Conditions (*Section* 2).—In reply to Mr. Lane we would explain that the general purpose and economics of the system are discussed in References 2–5 of the paper, and a later report presented to the Federal Power Board. It is not the object of the paper to discuss the overall economics, but we have referred to the economic factors which influenced the choice of voltage.

The fundamental purpose of the system is to deliver power from Kariba to the distant load areas in the south and north. Naturally the existing thermal plant at Salisbury, Umniati, Bulawayo and the Copper Belt must be coupled in and the best use made of it, but much of this plant will rapidly become obsolescent, and in a few years its importance will be relatively small.

Choice of Voltage (*Section* 3.2).—Mr. Lane expresses disappointment at the use of the 'non-preferred' standard voltage of 330 kV. We do not share his dismay, and consider that the standard-makers have erred in not providing a value between 300 and 400 kV; our view is supported by the fact that four other

systems are being established, at present, at or about 330 kV. On the other hand, there is only one system in the Western world at 380 kV, although on the Continent a number of early plans for the conversion of 220 kV lines to 380 kV are now being put into effect. Incidentally the 330 kV equipment in Rhodesia is mostly used at an altitude of nearly 5 000 ft, and its insulation therefore has a sea-level equivalent approaching that for 380 kV systems.

In reply to Mr. Newman, the systems in Fig. 2 were used for initial selection of voltage. Later it was considered a good investment to bring forward the date of the second line to Salisbery, as shown in Fig. 4.

Single-Pole Auto-Reclosing (*Section* 3.3.1).—The results of the switching tests given by Dr. Mortlock considerably influenced our decision to adopt single-pole reclosure.

Mr. Casson is mistaken in suggesting that 3-pole auto-reclosing would have been preferable on the mesh-connected section of the scheme, because, in fact, no auto-reclosing is either necessary or desirable on this section. On the Kitwe and Bulawayo single-circuit lines 3-pole auto-reclosing would have given an unacceptably low stability limit of 50 MW compared with one in the region of 200 MW with single-pole reclosing. Double-pole auto-reclosing was not considered in detail as the benefits are small compared with the relative complication.

Lightning Performance (*Section* 3.4).—Messrs. Newman and Parish question the shapes of the substation lightning protective areas. The zones of protection are based on model tests and on existing installations which are known to have given good performance. A single mast is taken to have a straight-sided cone of protection, the base radius being roughly equal to the height, but when an additional mast is added, the zone of protection is stretched out between the two and becomes appreciably greater than twice as large. Extensions of the straight parts of the boundaries shown in Fig. 7 do not pass through the positions of the towers.

From the best available data on lightning the number of strokes to ground (which is what matters) in the Kariba area is about twice that in the worst parts of America. We do not agree that the lightning precautions are extreme; the cost for a typical 330 kV substation area is about £1 600, which is a small premium to pay for what is hoped to be virtual immunity.

The surge diverters have been located underground mainly to give the maximum possible protection to the transformers. We agree that this arrangement makes the cable ends above the ground more vulnerable, and to compensate for this, the impulse level of the cables has been fixed at 1 500 kV, whereas that of the outdoor station is 1 350 kV.

Generators (*Section* 5.1.3).—The comparatively low synchronous reactance of the generators was chosen to ensure satisfactory operation at zero leading power factor and also to improve stability in the later stages of a disturbance, e.g. after the first swing. The cost of the generators is related to the choice of transient reactance and inertia constant as well as to the synchronous reactance, and, in this particular case, the additional cost of the low synchronous reactance is nothing like the figure of 20% suggested by Mr. Casson.

The use of high-speed automatic voltage regulators provides a margin of stability during a disturbance and also improves steady-state operation in the leading-power-factor region if the continuous thermal rating of the machine is exceeded for a short period.

330 *kV Cables* (*Section* 5.1.5).—Mr. Barnes's contention that a good case could have been made for gas-filled cables was not borne out in fact. Offers were received for both oil- and gas-filled cables, and the former were substantially cheaper.

Our normal practice is to require the impulse tests to be made on a hot cable, and Mr. Barnes is correct in suggesting that the comparatively low stress of 110 kV/cm under normal working conditions results from the high impulse test value chosen. The main reason for the low current density of these cables compared with those for the Snowy Mountains scheme would be apparent if we rechristened Kariba the 'Sunny Valley scheme'. High soil and air temperatures, bonding of the sheaths at both ends, extra reinforcement for the high static head and thicker insulation to withstand the high impulse test have all added to the cross-sectional area of the conductor, but the cost of this extra copper is very small.

330 *kV Switchgear* (*Section* 5.2.2).—In reply to Mr. Ratcliffe, the type of circuit-breaker to be used was left open in the inquiry. The final choice was made on economic grounds, to which a major contribution was made by the much greater compactness of the oil-circuit-breaker arrangement, resulting in an appreciable reduction in civil-engineering costs, particularly at Kariba.

We would explain to Mr. Newman that the rate of rise of restriking voltage of the system at about 10% fault current was found to be comparatively high. The values specified at 100% rating were extrapolated in line with typical characteristic curves for air-blast circuit-breakers. The oil circuit-breakers selected are fitted with resistors of such a value that the circuit-breakers are insensitive to r.r.r.v. over the whole range of fault currents. Mr. Bird may be relieved to know that air blowers are being provided to clear oil fumes out of the circuit-breaker tanks, and these will serve the added purpose of keeping the working conditions reasonably cool.

The specification called for a minimum diameter of 1·8 in for substation connections, which agrees closely with the value of 1·77 in mentioned by Mr. Smith. The switchgear manufacturers preferred a larger diameter for practical reasons, and in the absence of steel reinforcement, this seems to be a wise precaution.

Aluminium-to-copper connectors embody an insulating spacer between the two metals at the exposed junction. Such fittings have given good service for many years, even in the comparatively corrosive atmospheres of this country.

Details of the earthing arrangements at Kariba requested by Mr. Lane are as follows: All structures and metalwork in the underground station are coupled together by earth bars, and incidentally through the turbine intakes to the lake. A separate copper connection couples this system to the substation overhead, which itself is formed into a very large earthing mat by again coupling all plant, structures, foundations, etc., together into a common earth network.

Transformers and Reactive Plant (*Section* 5.2.3).—In reply to Mr. Bedil, the transport limit applied to the substation transformers. These are of the 3-phase type with on-load tap changing on the lower-voltage side, and weigh about 100 tons packed for shipment. The 3-phase type was not practicable for generator use because of transport considerations. The single-phase type ultimately adopted has a transport weight per unit of 92 tons.

Originally the reactors at Kariba were intended to be used on transformer windings temporarily disconnected from the generators, and parallel operation with the generators would undoubtedly have complicated the automatic-voltage-regulation equipment, as Mr. Newman suggests. Since the paper was written, these reactors have been eliminated as the generator installation programme has been advanced, and the design has shown ample margins in the under-excited region, especially in conjunction with the automatic voltage regulators. The generator overload capacity is sufficient to permit these margins to be used for the short periods when they may be needed.

Messrs. Lane and Casson criticize our approach to the use of series capacitors. The only major transmission system using series capacitors extensively is in Sweden, and both by action and words Swedish engineers have supported our view that series

capacitors serve best as an extending, reinforcing or balancing device, rather than as a prime measure. Mr. Ratcliffe also supports our view. We have been considering the use of capacitors on this basis, and the decision, when it is made, will be on economic grounds.

With regard to the use of synchronous compensators, it is mentioned in the paper that 20 MVAr units already exist at Kitwe. Nevertheless their cost is nearly ten times that of shunt reactors, and additional units could not be justified in the early stages. There is the further difficulty of starting compensators from a dead system.

The question of copper versus s.c.a. line conductors, raised by Mr. Austin, was reviewed by Mr. Ryle in the London discussion. With regard to the spacers, the absence of any moving parts is a great advantage; experience to date with these spacers is very good. With hinged spacers, wear at the pivots is likely to occur, particularly in dusty situations.

Although the higher impulse level of the total insulation would be of some value, timber or fibre-glass cross-arms would prove more costly than conventional steel construction, since span lengths, etc., would have to be much reduced on account of the lower mechanical strength of the cross-arm materials.

The normal foundation designs cover all 'average' ground conditions. In poor ground, e.g. that liable to be swamped in the wet season, special foundations are designed to suit local requirements. The straight-line tower design bearing pressure is restricted to 30 lb/in^2 (working value), and uplift is designed to be resisted by the weight of earth contained within a 30° frustum with a factor of safety of $2\frac{1}{2}$.

Protection, Communication and Similar Equipment (*Section* 5.4).—The emergency switching condition described by Dr. Mortlock is being catered for by over-voltage and excess-charging-current protection. Incidentally it is interesting that the automatic load-shedding scheme in the Copper Belt has operated successfully following the six interruptions of supply from the Congo that have occurred to date. Three single-phase faults on the 220 kV line have been reclosed successfully.

The replies to Mr. Casson's questions are that busbar protection is to be used at Kariba, and at Lusaka, two circuit-breakers are to be used, one in the line and one in the tee.

A special small computer is being provided in the control room to permit quick calculations to be made from the residual voltage and current indications. Calibration on site merely means that extensive tests will be made to establish a reliable working basis. It is not anticipated that the residual capacitive currents will affect the accuracy to an undesirable degree.

It does not seem surprising that Mr. Smith is having difficulty in obtaining carrier equipment of sufficient output to deal with phase comparison and distance protection, and we would expect the filter networks to be relatively complex and subject to appreciable attenuation. In Rhodesia we have to provide for distance protection only, and a simple h.f. signal is used which is coded where necessary, thereby permitting the use of more sensitive receivers. A major difference between Australian and Rhodesian conditions, so we understand, is that the Snowy Mountain protection carrier equipment has to operate at frequencies of 200–400 kc/s, whereas our equipment operates at frequencies down to 80 kc/s.

621.317.373 : 621.311.153.016.35

The Institution of Electrical Engineers
Paper No. 2602 M
Apr. 1958
©

A METHOD OF MEASURING AND DISPLAYING GENERATOR ROTOR ANGLE

By J. N. PREWETT, M.A., Graduate.

(*The paper was first received* 2nd *October*, 1957, *and in revised form* 29th *January*, 1958. *It was published in April*, 1958, *and was read before a joint meeting of the* Measurement and Control Section *and the* Supply Section 29*th April*, 1958.)

SUMMARY

The equipment was designed for stability tests at Cliff Quay generating station. The method chosen was one which might, with some modifications, be suitable for permanent installation in any power station.

The instantaneous angular position of the rotor is determined using photo-electric methods, and a reference voltage is derived from a voltage transformer connected either to the generator output terminals or to one of the station 132 kV busbars. The phase angle between these two electric signals is measured by a phase-sensitive detector using transistors, the d.c. component of whose output is used to drive a pen recorder having a high speed of response. The overall accuracy of the system is $\pm 6°$.

The photo-electric method has some disadvantages, and a magnetic method would be more suitable for long-term operation. Displaying rotor angle on a pen recorder is a very useful aid to the control engineer in determining whether his action is restoring generator stability.

(1) INTRODUCTION

The equipment to be described was developed to obtain rotor-angle measurements on two generators at Cliff Quay generating station during stability tests[1] held in 1956. It was required to provide with moderate accuracy an immediate and permanent record of rotor angle to assist the person in charge of the tests in making a rapid assessment of the previous test. In addition, it was decided to develop a system which could, with suitable modifications, be used in a permanent installation.

The majority of the methods of measuring rotor angle may be divided into three main classes, as follows:

(*a*) *Stroboscopic.*[2]—A gas discharge tube is energized from the generator voltage transformer to give a short-duration flash once a cycle. The lamp is arranged to shine usually on the end of the generator rotor, to which is fixed a disc marked in degrees. The disc appears to be stationary as long as the rotor angle is constant, while a change in rotor angle produces an equal rotation of the disc.

The value of rotor angle may be observed visually and by film recording,[3] the latter method being the only satisfactory one during periods of generator instability. The method is inherently accurate, but the developing and evaluation of the film can be a comparatively lengthy process.

(*b*) *Vector Synthesis Method.*[4]—The generator excitation voltage (which has a constant phase relationship with the rotor flux wave) may be synthesized by vectorially adding the generator terminal voltage to a voltage which would be obtained by passing the generator stator current through the generator synchronous reactance. The phase difference between this synthesized excitation voltage and the terminal voltage gives the rotor angle. The angle may be measured and displayed in a single instrument by using a power-factor-meter movement, or alternatively measured by a phase-sensitive detector and displayed on a milliammeter.

The method depends on the assumption that the generator synchronous reactance is constant. While this is true under steady-state conditions, it will vary under transient conditions. Therefore the method is only suitable for accurate measurements under steady-state conditions.

(*c*) *Rotor Angular Position Methods.*—An electric signal is obtained which is a function of the angular position of the rotor, and is compared in phase with the generator terminal voltage.

There are a variety of ways of obtaining the electric signal, such as an auxiliary commutator or a.c. generator fixed to the end of the generator rotor shaft, electromagnetic systems employing a pick-up head placed close to the rotor to which is attached a permanent magnet, and photo-electric systems employing alternate light and dark bands on the rotor.

A large number of phase-sensitive detector circuits exist, giving various output/phase-difference laws. When choosing a detector circuit, account must be taken of the type of indicating or recording instrument which is to be used. These include indicating meter, pen recorder and cathode-ray tube with camera.

Since the result of the recording was required immediately after the tests which were to include transient conditions, the stroboscopic and vector-synthesis methods had to be rejected in favour of one of the latter systems.

The system adopted employs a photo-electric cell whose output is modulated by light reflected from alternate light and dark bands on the rotor, an amplifier and phase-sensitive detector using transistors, and a pen recorder having a high speed of response. A record of constant increase of rotor angle consists of a linear increase for 180°, followed by a linear decrease for the next 180°. Because synchronous generators are only stable over a limited range of rotor angle, the ambiguity in the recording can be resolved. Errors of $\pm 6°$ were experienced in practice, but could be improved by using an electromagnetic pick-up on the generator, and a better phase-sensitive detector.

One of the main advantages of displaying rotor angle on a pen recorder was that a control engineer was able to see immediately whether a generator would regain synchronism after a transient stability test.

(2) FACTORS INFLUENCING THE DESIGN

(2.1) Supplies

When a generator loses synchronism, particularly if this is due to a system fault, the local supply voltage may vary considerably. Although the value of rotor angle was not required for the duration of a fault, it was essential that the reading immediately afterwards should not be influenced by the previous supply fluctuations. Therefore as much as possible of the equipment was operated from a battery supply, the remainder running off an auxiliary 240-volt petrol generator.

(2.2) Recorder

It was expected that the excess rotor speed over synchronous speed might reach 5 r.p.s. A conventional chart recorder has too slow a response speed, and a high-speed recorder (as

Mr. Prewett is at the Central Electricity Research Laboratories.

developed for electro-encephalographic work), having a response which was approximately flat from direct current to 90 c/s, was used.

(2.3) Method of Displaying Rotor Angle

The pen-recorder display can take three forms, depending on the type of phase-sensitive detector used. The three laws which the pen deflection can obey are as follows:

(*a*) A deflection which varies sinusoidally with rotor angle, one complete cycle corresponding to 360° change of rotor angle. This system permits the use of a recorder with the minimum speed of response, but the result is awkward to interpret owing to the sinusoidal law. Although there are two values of rotor angle to all pen positions, the ambiguity can always be resolved, because rotor angles between 150° and 350° are almost invariably unstable.

(*b*) A deflection which follows a symmetrical sawtooth law, one complete cycle corresponding to 360° change of rotor angle. For instance, there may be a linear increase in deflection with rotor angle from, say, 0° to 180°, and a linear decrease from 180° to 360°. The pen movement should have a response at least three times faster than in case (*a*). Rotor angle is now a linear function of deflection, and is easy to measure. As in (*a*), the ambiguity may be resolved.

(*c*) A deflection which follows an unsymmetrical sawtooth law, with output proportional to rotor angle over the range, say, 0° to 359°, and a rapid flyback between 359° and 360°. To obtain reasonable following of the input waveform where pole slipping occurs, the response of the pen movement should be at least ten times faster than in case (*a*). However, if the rotor angle is not accurately required in the unstable region, the flyback could be arranged to occur at a rotor angle of 180°, and a slower-response pen movement used. The deflection sensitivity (in degrees per centimetre) for a given maximum pen deflection is only half that in case (*b*).

Method (*b*) was chosen because of its linear response, higher deflection sensitivity and moderate demand on pen-movement response.

(2.4) Phase-Sensitive Detector

The requirements for the phase-sensitive detector are as follows:

(*a*) The output over the range 0–360° should be one cycle of a symmetrical sawtooth waveform.
(*b*) The output should not vary with changes of ±20% in reference voltage.
(*c*) The output should not vary with changes of ±20% in supply voltage.

Condition (*b*) requires that both the reference voltage and the rotor position voltage shall effectively be square waves. It is fortunate that condition (*a*) is now also satisfied.

It was decided that the easiest way of overcoming condition (*c*) was to operate the phase-sensitive detector from batteries, so that variations in mains supply voltage, especially under fault conditions, would not affect its output.

The output of a phase-sensitive detector is usually a complex waveform, which may be split into two components—one, a slowly varying d.c. component, is related to the phase difference between the two quantities being measured, and the other is an alternating component whose fundamental frequency is either the same as or twice the frequency of the quantities being measured, depending on whether a half-wave or full-wave type of detector is used. Where rapid changes of phase are expected, separation of the varying d.c. component from the unwanted alternating component is eased by making the fundamental frequency of the latter as high as possible. Therefore a full-wave type of phase-sensitive detector should be chosen.

(2.5) Rotor Position Pick-Up

A variety of methods are available for obtaining a signal which is related to the angular position of the rotor. Amongst those considered were the following:

(*a*) A small a.c. generator driven from the end of the rotor.
(*b*) A brush and commutator system mounted somewhere on the rotor shaft.
(*c*) A photo-electric method with black and polished bands on the rotor.

The extra mounting framework required for (*a*) and the possible high rate of wear in (*b*) make these schemes unattractive. Method (*c*) was therefore adopted.

(3) DESCRIPTION OF EQUIPMENT

The details of the system which follow are those used for the tests, and are not necessarily the best or most economical. As a result of these tests and the development of new techniques, a system suitable for a permanent installation is outlined in Section 6.

(3.1) Photo-Electric Head Unit

One half of the periphery of the rotor shaft was painted matt black, the remainder being a polished reflecting surface. The lamp and photo-transistor head unit shown in Fig. 1 was clamped

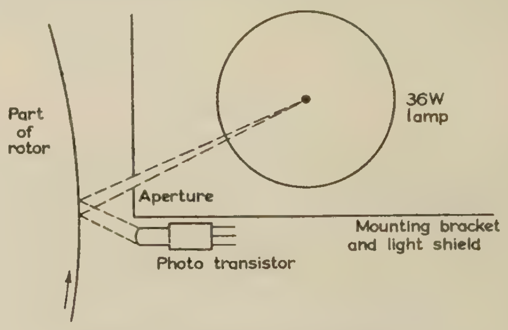


Fig. 1.—Photo-electric head unit.

to a rotor bearing housing, the photocell being ½ in from the rotor. Under these conditions, the 'light' current of the photo-transistor was 3 mA, the 'dark' current being reduced nearly to zero by base biasing.

(3.2) Phase-Sensitive Detector

A variety of full-wave circuits have been devised which use multi-electrode valves, diodes or transistors as the phase-sensing elements. It was decided to use transistors in the amplifying and phase-sensing circuits so that advantage could be taken of their high sensitivity and ability to operate from a low-voltage supply.

A simplified diagram of the original circuit is shown in Fig. 2. The 50 c/s square-wave output of the photo-transistor is used to drive transistors X1 and X4 in the same phase, and X2 and X3 in the opposite phase.

The square waves at A and B are therefore in anti-phase, the limits of the voltage swing being set by the battery voltage, since transistors X1–X4 are being operated as on-off switches. Transistors X5, X6 and X7, X8 are on-off switches which can pass current in either direction while in the 'on' condition. These two switches are driven in anti-phase by a reference voltage derived from a voltage transformer connected to some part of the power system.

The resultant current through the meter and resistor R is a 100 c/s square wave having a variable mark/space ratio. The

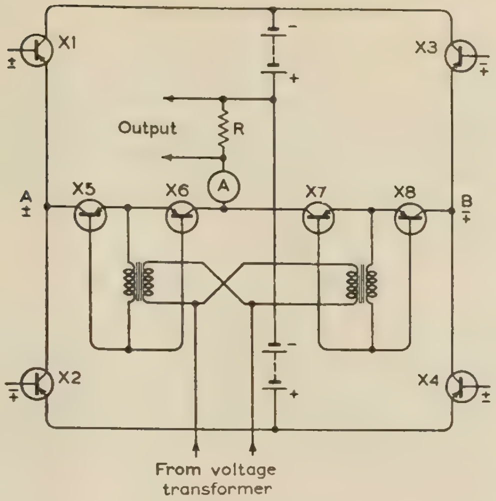


Fig. 2.—Simplified circuit diagram of phase-sensitive detector.

mean value of this current varies linearly with phase difference between the photo-transistor signal and reference signal over the range 0° to +180°. The particular 180° range desired in service may be varied by selecting an appropriate voltage as reference or by changing the relative position of the photo-electric unit and the bands on the rotor.

As the output of the phase-sensitive detector was insufficient to drive the pen recorder directly, a d.c. amplifier supplied from an auxiliary generator was interposed.

(3.3) Rotor-Angle Display

The peak-to-peak deflection of the pen was 3 cm, corresponding to a change in rotor angle of 180°. A convenient linear range of rotor-angle measurement seemed to be −30° to +150°, the sense of the deflection reversing from 150° to 330°. The chart speed was 3 cm/s.

Fig. 3 shows a copy of an actual result. The solid line is the

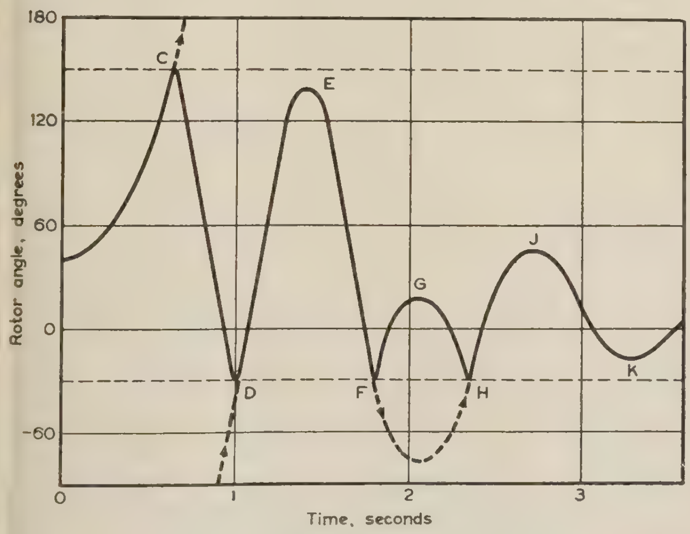


Fig. 3.—Copy of a rotor-angle recording showing pole slipping and rotor-angle oscillation.

——— Actual record.
– – – – Record replotted on a 360° scale.

trace made by the pen, while the dotted lines are those which would have been traced by an instrument having a linear range of 360° with an instantaneous flyback [as in Section 2.3(*c*)]. Rapid changes of direction of the solid-line trace, as at C, D, F and H, are changes in sense of the output of the phase-sensitive detector. The slower changes at E, G, J and K are oscillations of the rotor angle. This record shows that the generator rotor slipped forward one pole pair in the first second after the start of the record, followed by violent but rapidly diminishing oscillations of rotor angle.

(4) COMPARISON OF RESULTS

In three of the tests, the measurements made by this system were duplicated by a stroboscopic method used in conjunction with film recording, in which the angle can be read accurately to the nearest degree.[5] The limits of rotor-angle oscillation obtained by the two methods are compared in Table 1.

Table 1

Comparison of Rotor Angle Measurements by Two Methods

Observation No.	Rotor angle		Difference
	Photo-electric method	Stroboscopic method	
	deg	deg	deg
65	54	54	0
	150	138	12*
	21	19	2
	100	95	5
	45	44	1
	74	72	2
66	40	38	2
	140	129	11*
	−78	−87	9
	46	44	2
	−20	−26	6
	24	24	0
67	52	52	0
	147	135	12*
	2	−1	3
	75	71	4
	27	27	0
	45	45	0

The differences marked with an asterisk occur where the output of the phase-sensitive detector is about to change sense. The errors at these points may therefore be expected to be greatest. Elsewhere, the agreement between the two methods is considered to be satisfactory, and could be improved by using a more suitable pick-up for obtaining instantaneous rotor position.

(5) APPLICATIONS

During these tests, it was found that indicating meters were almost useless for determining whether generator stability had been restored after a large oscillation of rotor angle, owing to their slow speed of response and resonance effects, or the inability of the human eye to follow the rapid oscillations of the pointer of a meter having an adequate response. Even observations of the stroboscopically illuminated disc on the end of the generator rotor gave misleading results owing to the speed of 'apparent rotation' of the disc immediately following a severe system fault. Using a fast-response pen recorder to measure rotor angle gave a clear and immediate indication of whether pole slipping had occurred and stability was being restored, and was the only satisfactory instrument available to the control engineer during the period of large rotor-angle oscillations. At stations where

instability is liable to occur at any time, a permanent rotor-angle measuring installation could be installed, provided that certain modifications outlined in the next Section were made.

(6) MODIFICATIONS FOR A PERMANENT INSTALLATION

The photo-electric method of determining the instantaneous position of a rotor is not satisfactory for long-term use, because the reflection from the black and reflecting bands is spoilt by the accumulation of dirt and oil. A better method developed in Canada[6] uses a magnetized band of steel tape around the rotor and a magnetic pick-up to determine instantaneous rotor position. Initially the pick-up is energized from the generator voltage transformer while the generator is running off load. This process magnetizes the steel strip sinusoidally, so that when the generator rotor angle is zero the voltage subsequently induced in the pick-up has a known phase relationship to the original exciting voltage. As the rotor angle varies, this phase difference will alter by the same amount. One of 12 possible connections is made to the voltage transformer to obtain a reference voltage so that the recorder covers a convenient 180° range of rotor angle. Future phase-sensitive detectors would use a more economical circuit consisting of two coincidence detectors to give a full-wave d.c. output proportional to the phase difference between the two electrical inputs. The supply voltage could be stabilized with a Zener diode.

It would be impractical to have a pen recorder continuously using paper at the rate of several centimetres a second, so that an automatic start should be incorporated which operates when the rotor angle exceeds, say, 75°. An automatic stop might also be provided, which would turn off the recorder a few seconds after the reduction of rotor angle below 65°. As the paper would be stationary for long periods, ink recording should be replaced by a system using paper sensitive to scratching, an electric current or ultra-violet light. The type of pen movement used is a compromise between adequate response and power required to drive the movement. A response which is substantially flat up to 5 or 10c/s is probably the best solution. It should then be possible to drive the pen from a low-power transistor amplifier.

(7) CONCLUSIONS

The overall system proved satisfactory for the duration of the tests, and displaying rotor angle on a fast-response pen recorder during the period of generator instability was found to be the most satisfactory method. Future installations would use a magnetic pick-up to obtain instantaneous rotor position rather than the photo-electric method described. With suitable modifications, the system is suitable for permanent installation in a generating-station control room.

(8) ACKNOWLEDGMENTS

The author wishes to acknowledge the helpful suggestions of Messrs. E. F. Hasler and J. E. Toms in the experimental work, and the assistance of the staff at Cliff Quay generating station during the tests. Thanks are also due to the Director of the Central Electricity Research Laboratories, for permission to publish the paper.

(9) REFERENCES

(1) BUSEMANN, F., and CASSON, W.: 'Results of Full-Scale Stability Tests on the British 132kV Grid System', *Proceedings I.E.E*, Paper No. 2575 S, February, 1958 (**105** A, p. 347).

(2) PRESCOTT, J. C., and CONNON, E. W.: 'Measurement of the Load Angle of Synchronous Machinery', *Journal I.E.E.*, 1931, **69**, p. 281.

(3) POWELL, E. B.: 'The Diagnosis of Steam Turbo-Alternator Performance by Stroboscopic Methods', C.I.G.R.É., Paris, 1956, Paper No. 101.

(4) VERNON, K. R.: 'The Development of a Generator Stability Meter', South East Scotland Division Report, October, 1954.

(5) POWELL, E. B., and HARPER, M. E.: 'Generator Rotor Angle Measurement by Stroboscopic Means' (see next page).

(6) WOODHEAD, L. W.: 'Load Angle of Synchronous Machines', *Ontario Hydro Research News*, July–December, 1956, **8**, p. 21.

[The discussion on the above paper will be found on page 617.]

621.317.772 : 621.311.153.016.35

The Institution of Electrical Engineers
Paper No. 2576 M
Apr. 1958
©

GENERATOR ROTOR ANGLE MEASUREMENT BY STROBOSCOPIC MEANS

By E. B. POWELL, M.I.C.E., M.I.Mech.E., Member, and M. E. HARPER, Associate Member.

(*The paper was first received* 17*th October*, 1957, *and in revised form* 6*th January*, 1958. *It was published in April*, 1958, *and was read before a joint meeting of the* MEASUREMENT AND CONTROL SECTION *and the* SUPPLY SECTION 29*th April*, 1958.)

SUMMARY

The stroboscopic equipment described in the paper was originally designed and used for observation of machine rotor angles under conditions where recording was not required. Further development of the apparatus, together with the establishment of a ciné-film recording technique, extended its use to the recording of rapid rotor-angle changes.

The general principle of the observation of rotating machinery by stroboscopic methods is, of course, well known. In this application, the flashing light source is triggered once per cycle by a voltage obtained from a voltage transformer. The particular voltage transformer chosen will depend upon the primary voltage with which it is desired to compare the machine rotor movement.

A ciné camera driven at 50 frames/sec is used to obtain a ciné-film recording of the stroboscopic image. This permanent pictorial record of the rotor movement during the period of observation may be projected on to a screen in the usual way, or an angle/time curve may be drawn from an inspection of the film.

The particular value of this method lies in the accuracy with which very rapid changes of rotor angle are recorded. It suffers from a disadvantage, since viewing of results is delayed until the film has been developed.

The apparatus has been found most helpful in a number of transient tests on turbo-generators.

(1) INTRODUCTION

The use of stroboscopic flash equipment for determining the relative movement between the rotor of an alternator and the rotating field of its stator was first adopted in the London Division of the Central Electricity Generating Board* in 1953. This was to determine whether load fluctuations on certain machines were due to erratic turbine governing or the high impedance of the main transmission system.

In these original tests a single narrow white band, which had been painted on the machine coupling, was observed stroboscopically. By this means it was possible to tell whether the machine rotor was tending to accelerate or decelerate with reduction in output, and so decide whether this load variation was due to the system characteristics or the turbine governor.

From these initial tests it was clear that the incorporation of a phase-shifting circuit would be advantageous, in order that the angular movement of the rotor could be accurately determined under various loading conditions. This circuit is not generally available in commercial equipment, and it was decided to build an experimental stroboscope for fixed-frequency working in which this feature would be incorporated. The new equipment was used during certain steady-state and transient tests, and it became evident from the results that a permanent record of the shaft movement was necessary, since visual observation alone was not completely satisfactory, even when the rate at which the rotor moved was relatively slow. The obvious solution was to try to photograph the stroboscopic image. A number of still photographs were taken, from which it was found that the light source from the stroboscopic flash equipment was adequate.

In view of these results, further tests were carried out on a 15 MW 1 500 r.p.m. turbo-alternator under steady-state and transient conditions, using a ciné camera to photograph the stroboscopic image obtained from black and white bands painted on a 6 in. disc fastened to the end of the alternator shaft. The film, which was taken in the turbine hall of one of the older generating stations, without any special screening precautions against direct lighting, proved to be entirely satisfactory.

As a result of these tests, the equipment described in the paper was designed.

(2) DESCRIPTION OF EQUIPMENT USED ON TESTS AT CLIFF QUAY

(2.1) Stroboscopic-Flash-Equipment Reflecting Surface

The usual fitting to the machine is a disc made from 16 gauge aluminium which is mounted on the exciter end of the shaft.

The disc, which is 12 in in diameter, is covered with a specially prepared material on which crystalline particles have been deposited to give good light reflection properties. Markings on the disc consist of black radial lines around the circumference indicating 0 to 360° with figures at every 10°.

If the shaft end is not available, as in the case of a machine with a geared exciter, the shaft may be marked circumferentially 0–360°, or a similarly marked strip of reflecting material fixed around it. This method has proved to be quite as satisfactory as the reflecting disc.

(2.2) Circuits for Stroboscopic Flash Equipment

With the following exceptions the circuits are standard. The trigger input circuit has provision for external triggering at 110 or 230 volts, thus enabling any system reference voltage to be used. This triggering supply is connected to a transformer which delivers 325 volts (r.m.s.) to an *RC* phase-shifting network, consisting of a 200-kilohm wire-wound potentiometer in series with a $0 \cdot 05\,\mu$F condenser.

The centre tap of the *RC* network feeds a type SP 61 valve, via a 1-megohm grid-limiter resistor. This enables the valve to be used as a signal squarer, and at the same time to provide a large-amplitude output signal which is fed to a differentiating network. The derived signal triggers in the usual manner the grid of a type EN 40 stroboscopic flashlamp, which is suitable for photographic purposes.

The phase-shifter described enables the external trigger signal to be moved through 55° of arc, and when used in conjunction with a supply which may be obtained from any one phase of a 3-phase voltage transformer, provides a wide range of angular adjustment. By this means it is possible to arrange that the stroboscopic flash always occurs reasonably near the middle of the half-cycle during which the camera shutter is open. This ensures that any phase shift between the works power voltage energizing the camera motor, and the triggering supply, is immaterial. In meeting this condition, however, it was not

* Then the British Electricity Authority.

[Th]e authors are with the Central Electricity Generating Board (London Division).

possible also to set the strobe disc angle to zero simultaneously with the machine zero load, and an arbitrary zero load angle had therefore to be tolerated.

The schematic of the equipment is shown in Fig. 1, from

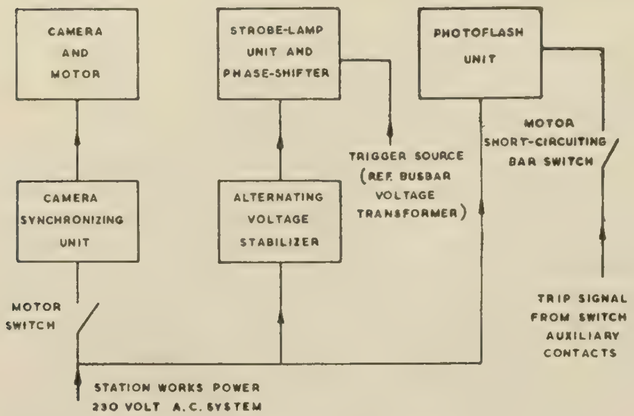


Fig. 1.—Schematic of equipment.

which it can be seen that the stroboscopic-unit power supplies are obtained from a simple saturated-core a.c. stabilizer fitted with third- and fifth-harmonic filters. The stabilizer is fed from the works power board, connected to the main busbar system, and the camera motor supply is taken unstabilized from this same source, via the camera synchronizing unit.

The stroboscopic flashlamp trigger voltage, however, is derived from a voltage transformer on the desired reference system, and is therefore completely independent of works power fluctuations.

The accuracy of this method of measuring load angle depends entirely on the repetitive constancy of the flash, and any phase shift in the trigger signal will introduce errors. This signal must come from a voltage source connected to the reference busbar, which will, under fault conditions, suffer reduction in amplitude and some waveform distortion. It was necessary, therefore, to test the equipment to determine the effect of such changes on the accuracy.

The relationship between the amplitude of the trigger voltage obtained from the reference system and the phase-angle occurrence of the flash is shown in Fig. 2. It will be seen that with a normal voltage transformer supply of 110 volts, a voltage change of +10 to −50 volts produces a change in phase angle of less than 1°. The lamp continues to operate down to a trigger voltage of 10 volts (r.m.s.). The shape of the voltage/angle curve is entirely due to the design of the input trigger transformer.

Fig. 3 shows the effect upon the accuracy of the strobe calibration of 5% of third-harmonic distortion present in the triggering signal. It will be noted that this produces a maximum phase-angle error of ±3°. The phase-angle error actually produced in any instance, however, is entirely dependent upon the phase-angle relationship between the fundamental and the harmonic content present. This is because the lamp trigger is synchronized to the first 6 volts of the negative-going half-cycle of the fundamental waveform, and provided that the phase angle of the harmonic present is such as to have no effect upon this critical part of the fundamental waveform, little error will occur. Further tests taken with the same

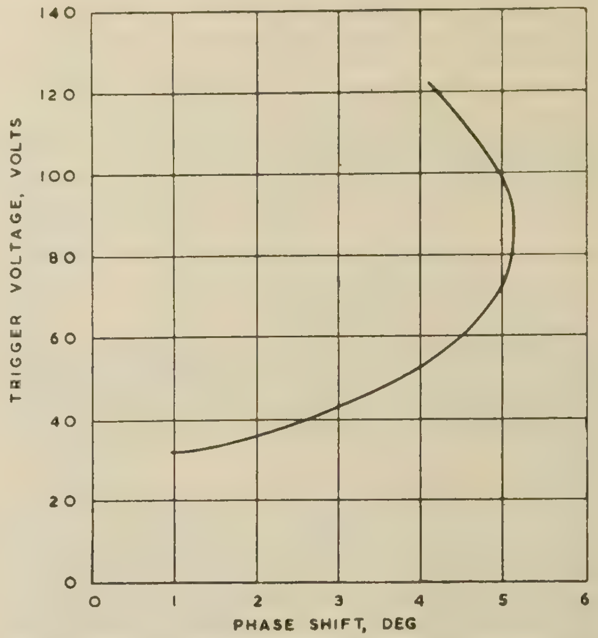


Fig. 2.—Effect of trigger voltage on phase relationship of the stroboscopic flash.

percentage of fifth and seventh harmonics present produce similar results.

(2.3) Camera Drive

In order that the flash from the lamp can be photographed, it is essential for the camera to be driven at a speed precisely matched to the flash frequency. This was achieved by removing the hand drive and fitting a small synchronous motor, the camera speed control being made inoperative by setting it at 64 frames/sec. A single-phase 230-volt capacitor motor was chosen, which produced a continuous torque of $6\frac{1}{2}$ oz-in, running at 3 000 r.p.m., a suitable gear drive being designed and fitted.

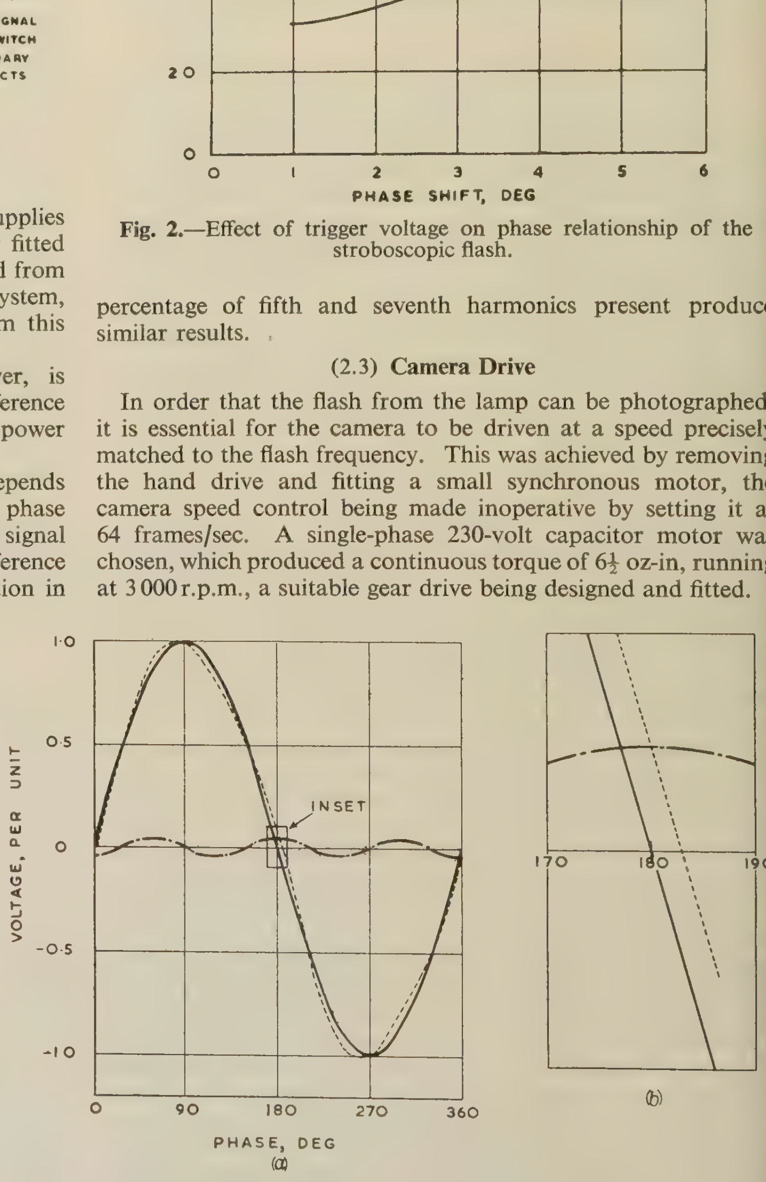


Fig. 3.—Effect of third-harmonic distortion of the trigger signal on the phase relationship of the stroboscopic flash.

——— Fundamental.
– – – – Fundamental plus third harmonic.
—·—· Third harmonic.
(*a*) Main curve.
(*b*) Inset on (*a*) magnified ten times.

(2.4) Synchronizing Camera Shutter and Stroboscopic Flash Equipment

As it is essential to ensure that the camera shutter is always open when the flash occurs, and as the motor can pull into synchronism in two positions, 180° apart, a special selective synchronizing system had to be adopted. Details of this system, which is shown in Fig. 4, are described below.

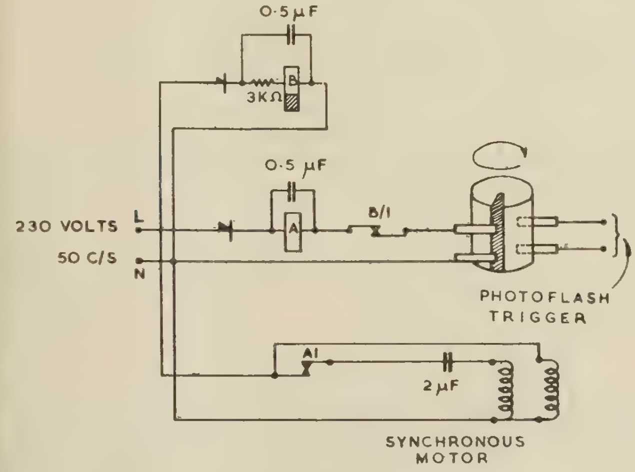


Fig. 4.—Circuit of camera synchronizing unit.

Relay A. 1 000 ohms + 1 000 ohms, 3000 type, parallel.
Relay B. 270 ohms + 270 ohms + 3T. LP104979/TFG series, 1in toe slug.

An insulated bush, to which a single brass segment is fitted, is mounted on the shaft of the motor. This provides a simple short-circuiting bar for a pair of suitably mounted brushes, which are connected in series with a relay and a half-wave metal rectifier across the 230-volt mains supply. The relay contacts are connected in series with the condenser-fed phase of the motor. The polarity of the rectifier is such that, if the motor synchronizes incorrectly, the mains supply fed via the brushes and short-circuiting bar will cause the appropriate half-cycle to energize the relay via the rectifier. The relay contacts will then disconnect one phase of the motor, and it has been found that such an interruption causes the motor to slip through 180°.

In Fig. 4, relay A selects the true synchronizing position of the motor, and relay B is incorporated to delay the operation of relay A during the running-up period. This circuit, which is by no means critical in adjustment, operates extremely well, and experience has shown that the camera can be correctly synchronized within a time of 2 sec.

(2.5) General Assembly

The stroboscopic flash equipment is mounted on, and to the rear of, the camera unit in such a manner as to illuminate both the synchronizing gear and the disc mounted on the alternator shaft. The insulated bush on the camera-motor synchronizing gear is marked with a small white spot, by means of which a stroboscopic check is kept on the synchronism of the camera motor.

(2.6) Ciné-Photography

A 2 in lens is used, stopped at f 4·5, the distance of the camera from the disc being 3 ft. Under these conditions, and using a type EN 40 lamp and HP 3 film, results have been entirely satisfactory. Owing to the low stop number and proximity of the disc, special care has to be taken with camera focusing.

It is necessary for some marker signal to be recorded on the film to show the instant at which the test started, since a considerable length of film may have been run off before this point. A photographic flash unit is therefore used, to black out the appropriate frame on the film, and this is triggered by a pair of auxiliary contacts from the fault initiating switch, or other similar starting device. To ensure that the flash so triggered does not occur during the period when the camera shutter is closed, this trigger signal is fed through a second pair of brushes, which in turn are short-circuited by the brass segment on the spindle of the camera motor.

(2.7) Precautions against Direct Illumination

With the photographic settings described, satisfactory film recording can be obtained under the normal lighting conditions of a turbine hall. Should the disc be mounted in a position where it may receive direct artificial light or sunlight, it is necessary for screening to be provided.

(3) ANALYSIS OF RESULTS

Examination of the film is carried out by passing it through a film editor or viewer, which projects the image, enlarged approximately ten times, on to a glass screen. The film is wound through the viewer by hand, and may be seen as a whole or examined frame by frame.

A mechanical frame counter was designed and built into the viewer, to assist in the inspection of the film at regular intervals. This counter also makes it easy to refer back to a previous frame whenever necessary, and has contributed greatly to the ready handling of the film.

Analysis of the film varies according to the nature of the record and with the type of information required. In general, however, where the rotor is changing speed in a uniform manner, examination of every fifth or even tenth frame gives sufficient points for the drawing of an angle/time curve. Special attention is required where a very rapid change of speed occurs, or where there is a change from acceleration to deceleration, and at these points examination of every frame may be necessary.

A complete test record rarely lasts more than 30 sec, giving a film length of 40 ft. This film can be examined, and the angular movement logged, in less than half an hour.

From the readings of angular movement an angle/time curve is produced which illustrates the behaviour of the rotor during the test; a sample of such a curve is shown in Fig. 5.

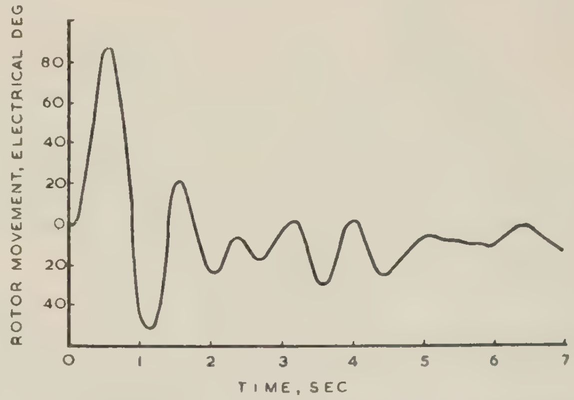


Fig. 5.—Typical angle/time curve obtained from a film taken during a 3-phase fault.

Machine running at full load.
Fault duration: 0·32 sec.

(4) APPLICATION

The apparatus is of great value in connection with investigations into the behaviour of machines where switching of

fault transient effects are to be observed, and where accurate rotor-angle-movement recording is required for the initial few cycles.

In machine testing generally, where a very rapid acceleration or deceleration is expected, this method would also be applicable. For example, when running with a heavily-advanced rotor angle, there is a possibility of the machine becoming unstable, and it may be desired to obtain an accurate picture of rotor movement from the commencement of instability.

In certain cases of turbo-generator performance, where it is necessary to observe small rotor oscillations of the order of 2–3°, the method described has also proved successful.

Again, the equipment has been used to obtain records of speed change for the purpose of calculating the stored energy of machines. Since an accurate record of angular change over the first $\frac{1}{2}$ sec can be obtained, the acceleration constant derived from this record may be used for the calculation of stored energy. By carrying out a load-rejection test at a small percentage of the generator rating, the possibility of steam valves operating in such a short time as $\frac{1}{2}$ sec is avoided, and the accelerating force can for practical purposes be assumed constant.

Some examples of the use of the instrument are described in Reference 3.

(5) MODIFICATIONS TO FUTURE EQUIPMENT

A new phase-shifter has been built around a 3-in Magslip resolver. This is much simpler to operate, and provides coverage for a full 360°.

The capacitor motor has been replaced by a 3-phase type, giving increased running torque of 11 oz-in, and having the following advantages.

First, the extra torque available permits the use of larger film spools, and the camera, which previously could take only 100 ft spools of film per loading, has been modified to take spools of 400 ft.

Secondly, the motor can be made to synchronize at six different positions, three of them being achieved by rotating the phase connections, and a further three by arranging that relay rectifier A (Fig. 4) can easily be connected in reverse. It is simple, therefore, to fix the position of the flash with respect to the camera shutter to the nearest 60°. The new phase-shifter can now be used to enable the equipment to show zero degrees on the stroboscope reflecting disc with the machine operating at no load.

A disc, marked with an arrow, is now fitted to the top of the camera-motor spindle, and surrounded by a fixed circular scale marked 0–360°. This arrangement makes it possible to strobe the load angle of the camera motor on a continuous basis, and to use the angle indicated, for checking that the phase angle of the stroboscopic flash equipment remains constant. The observed angle of the camera motor also provides an assurance that the synchronizing relay has operated satisfactorily and that the motor is correctly synchronized.

(6) CONCLUSIONS

This method of rotor angle measurement depends on the assumption that the stroboscopic lamp can be made to operate at exactly the same instant in each cycle. Under normal operation this can be assured, since it has been observed from tests on a number of machines connected to various networks that the angle of the rotor does not vary more than $\pm 0\cdot 1°$ under any steady load conditions. Any error introduced into the marking of the reflecting disc can, of course, be neglected, since $1\cdot 0°$ occupies an arc of $0\cdot 1$ in on the periphery, and even with careless marking the error will not be more than $0\cdot 005$ in. The maximum error that is likely to occur under steady-state conditions is therefore $\pm 0\cdot 1°$.

Under transient conditions an error of $\pm 1\cdot 0°$ may be introduced by voltage variations on the reference busbar (see Fig. 2). This would occur only under very severe fault conditions, however, and under normal testing conditions the error that may be expected under voltage variations should be within $\pm 0\cdot 5°$.

The greatest cause of error is the distortion of the waveform, as shown in Fig. 5. With a system which has a bad waveform this will not cause any error as long as the waveshape remains constant, which will probably occur under steady-state conditions.

Under initial transient conditions during short-circuits on the system, it has been found that an error of probably $\pm 2\cdot 0°$ or $3\cdot 0°$ can occur during the first few cycles, but after this short period has passed the error due to transients can be neglected.

From the above, the authors are confident that the accuracy to be obtained with this type of angle-measuring equipment will normally lie between $\pm 0\cdot 5°$, except during the first three cycles under fault conditions, when the error may increase to $\pm 3\cdot 0°$.

This stroboscopic equipment is therefore of particular value in recording very small or rapid changes in rotor angle. It gives a true record of such movement and can be classed as a precision instrument.

Whilst the apparatus affords this high degree of accuracy, it has the disadvantage that the test results are not available until after the film has been developed. This weakness is avoided in the equipment described by J. N. Prewett,[2] which makes the information immediately available in the form of a chart recording.

The authors consider, however, that, where a high degree of accuracy is essential to the purposes of the investigation, the stroboscopic method is preferable.

(7) ACKNOWLEDGMENTS

The authors wish to express their appreciation of the assistance and suggestions received from their colleagues in the London Division of the Central Electricity Generating Board, and for the help received from the Eastern Divisional Staff at Cliff Quay during the tests carried out there.

Thanks are also due to the British Rayon Research Association for permission to use the basic principles of their motor synchronizing relay, and to the Controller of the London Division for his kind permission to publish the paper.

(8) REFERENCES

(1) BUSEMANN, F., and CASSON, W.: 'Results of Full-Scale Stability Tests on the British 132 kV Grid System', *Proceedings I.E.E.*, Paper No. 2575 S, February, 1958 (**105** A, p. 347).

(2) PREWETT, J. N.: 'A Method of Measuring and Displaying Generator Rotor Angle' (see page 605).

(3) POWELL, E. B.: 'The Diagnosis of Turbo-Alternator Performance by Stroboscopic Methods', C.I.G.R.É., Paris, 1956, Paper No. 101.

[The discussion on the above paper will be found on page 617.]

621.317.772 : 621.311.153.016.35

The Institution of Electrical Engineers
Paper No. 2598 M
Apr. 1958
©

POWER-SYSTEM PHASE-ANGLE MEASUREMENTS

By F. MORAN, M.Sc., A.Inst.P.

(*The paper was first received* 1*st November*, 1957, *and in revised form* 24*th January*, 1958. *It was published in April*, 1958, *and was read before a joint meeting of the* Measurement and Control Section *and the* Supply Section 29*th April*, 1958.)

SUMMARY

The paper describes an instrument developed to record the phase variations between two 50c/s signals with a scale of $\pm 12\frac{1}{2}°$. The instrument was used during generator stability tests to record phase variations between the reference busbar voltage and a voltage at a remote point in the system undisturbed by the tests. The measurements were required to correct the test-generator rotor-angle measurements.

(1) INTRODUCTION

The instrument described in the paper was specially developed for use in connection with the generator stability tests held by the Eastern Division of the Central Electricity Authority at Cliff Quay over the period 4th–7th August, 1956.

A recording was required of the phase variations of the voltage of the system (black) busbar at Cliff Quay compared with the voltage at a remote point in the system. The system busbar voltage at Cliff Quay was being used as a local reference vector for machine rotor-angle measurements, and the additional measurement of variations in the local reference vector was needed to refer the machine rotor-angle measurements to a standard unaffected by the tests for all practical purposes.

Preliminary network-analyser studies suggested that the variations to be expected would be oscillatory at a frequency not greater than 1 c/s and of an amplitude not greater than $\pm 10°$.

The instrument was therefore designed to give a direct pen recording of phase angle with a scale of 25° on an 11 in chart. It was also designed to be as free from drift as possible, and to be insensitive to variations in amplitude of the voltages being compared. The last requirement was important since the Cliff Quay voltage was expected to vary by up to 10% of the nominal value at the critical instant of measurement.

The simplest phase comparator considered was a phase-sensitive bridge comparing sinusoidal signals. The output of such a circuit is a measure of the phase difference of the input signals, but the relationship is usually not linear and is dependent on the amplitude of the input signals. Both limitations made this an unsatisfactory approach.

Consideration was next given to a servo-driven phase-shifter which was available. The sensing circuit for the servo-amplifier was a phase-sensitive bridge, but as the servo mechanism balanced this to a null output the overall measurement of phase was practically independent of input amplitude. However, the response time of the mechanical system was unsatisfactory for the anticipated rate of variation of phase.

The effect of amplitude variation could be overcome by squaring-up the inputs, which would also lead to a linear calibration in a square-wave comparator. The instrument was therefore designed on this basis.

There are numerous references to the methods that can be used for phase comparison. In Reference 2 Farren describes simple phase-comparing circuits using both sine and square waves and concludes that, where linearity of response is desired, the latter shows advantages. There have been many instruments described which employ calibrated phase-shifters,[3] and an elaborate instrument in which the phase-shift measurement is effectively converted to a voltage measurement has been described by Kritz.[6] Other methods have included those based on the determination of the ratio of the sum and difference of one voltage and the in-phase component of the second[5,14] giving a measurement claimed to be independent of frequency. A method using a sawtooth generator to measure the time between the zero intercepts of the two signals is discussed by Yu.[7] The frequency must be known precisely, but only one cycle is required for the measurement. The use of a magnetic amplifier as a phase comparator has also been discussed by Sukurai and Nagano.[11] However, none of these methods lend themselves to high-speed recording of signals which may be subject to rapid amplitude fluctuations.

Instruments in which the sine waves are converted to square waves of which the leading edges are used to trigger multivibrators include those due to Kruse and Watson,[4] Vanden Dooren[13] (with a Cartesian co-ordinate display) and Homilius,[12] but difficulties in triggering have been experienced at small phase differences. Finally there are a group of instruments[9,10,15] in which the square waves are mixed in some way and the resultant waveform is suitably integrated. The last of these papers was not available to the author at the time the work was undertaken. For instruments in the last group the preservation of unity mark/space ratio is important, and that due to Moss employs a feedback circuit[8] to preserve this unity. The rate of response in face of signal-amplitude changes is restricted by the smoothing necessary between the discriminator and d.c. amplifier in the feedback loop, and this circuit was not therefore used by the author. Instead the a.c. signal level was increased to 800 volts (d.a.p.) before application to the squaring stages which preserved the mark/space ratio sensibly constant over a 10 : 1 range of input voltage with no undesirable transient effects. The large alternating voltage required was obtained by stepping up the output of an audio-frequency amplifier by a factor of 10 : 1 in a suitable transformer, and as it was known that the amplifier was capable of at least twice the required output without distortion, the preservation of the mark/space ratio was ensured under the worst transient conditions anticipated. The circuit described by Haller[10] is interesting in that it uses a special gating valve (type EQ80) to mix the signals, the quoted maximum error being 3°.

The purpose of the paper is to describe the method used for making a high-speed recording of small phase-angle variations, and no attempt will be made to interpret or discuss the results obtained during the Cliff Quay tests, since all the data accumulated have been analysed as a whole and considered in Reference 1. However, some examples of the measurements made will be included in this paper as illustrations of the performance that can be expected from the instrument.

Mr. Moran is at the Central Electricity Research Laboratories.

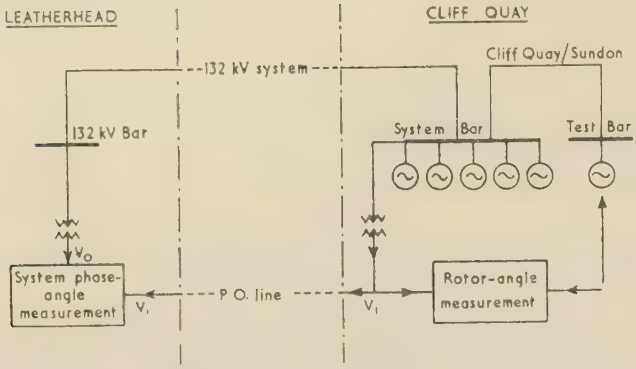


Fig. 1.—Schematic of system phase-angle measurement.

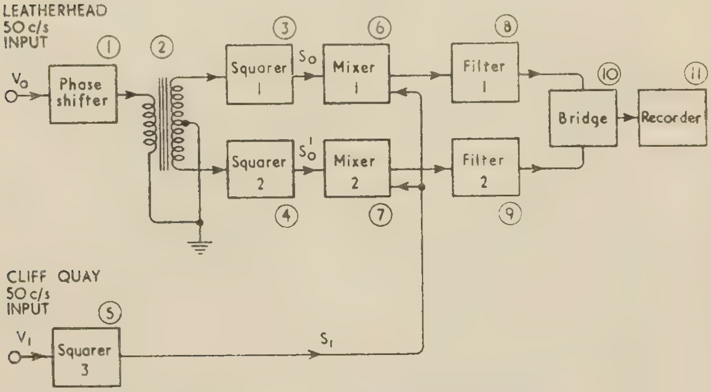


Fig. 2.—Block schematic of phase-angle recorder.

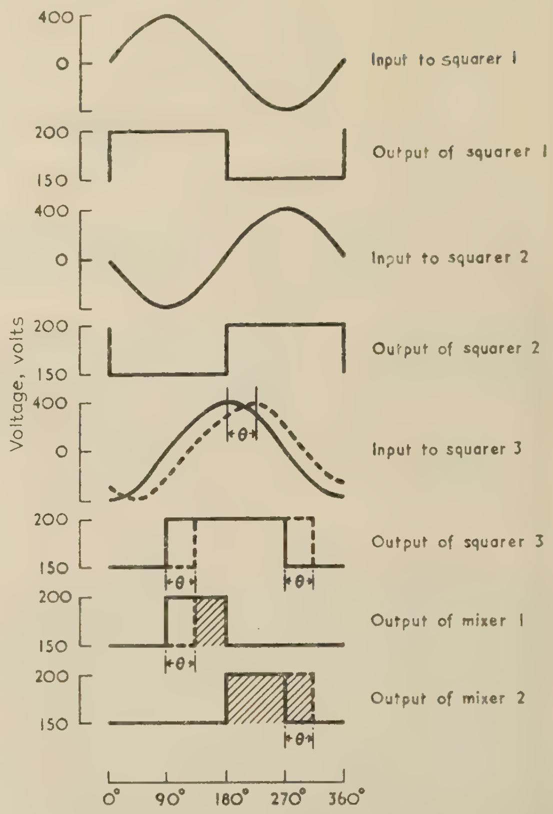


Fig. 3.—Squarer and mixer waveforms.

(2) METHOD OF OPERATION

The two voltage vectors to be compared are V_0, the reference, and V_1, the unknown. In the Cliff Quay tests (see Fig. 1) V_0 was derived from the Leatherhead 132 kV busbars and V_1 from the Cliff Quay system busbar and transmitted to Leatherhead over a Post Office telephone line as modulation on a 2·56 kc/s carrier.

The voltage V_0 after passing through the phase-shifter 1 (see Fig. 2) is applied to the primary of transformer 2. The phase-shifter can be adjusted to bring the instrument to mid-scale prior to making a recording. The recorder will then register phase variations of up to $\pm 12\frac{1}{2}°$ between the two voltages with respect to this datum.

The two outputs from transformer 2 are in anti-phase and are individually squared in the squaring stages 3 and 4. Similarly the voltage V_1 is squared in stage 5. The nominal input voltage to each sine square-wave convertor is 230 volts (r.m.s.). There is no detectable change in output waveform down to about 20 volts (r.m.s.). There are no *RC* couplings in the squaring stages, and, consequently, sudden changes in input voltage cannot affect the levels of the output waveform and produce spurious responses on the recorder.

The square-wave outputs S_0 and S_1 from stages 3 and 5 are mixed in stage 6 to produce an output rectangular wave, the mark/space ratio of which is determined by the relative phases of S_0 and S_1, as shown in Fig. 3. Similarly the output S_0' (which is in anti-phase to S_0) is mixed with S_1 in the mixer stage 7. If the input voltages V_0 and V_1 are in quadrature the outputs of the mixer units will be identical in shape but displaced in time, as shown in Fig. 3. To eliminate any unbalance in the squaring stages the mixer outputs are limited using a common reference voltage before being compared.

The resultant square waves from the limiters have positive and negative levels of 200 and 150 volts, respectively, and positive and negative durations of 90° and 270° of one supply cycle for the initial condition of V_0 and V_1 in quadrature. The mean d.c. levels of the two limiter outputs will then be equal. However, if the phase of V_1 measured with respect to V_0 changes by θ, the mean d.c. levels of the limiter outputs will no longer be equal since the positive and negative durations of one output will be $(90 + \theta)°$ and $(270 - \theta)°$, respectively, and of the other $(90 - \theta)°$ and $(270 + \theta)°$, i.e. the mean d.c. output of one limiter will rise and the other will fall. Also the difference between the two outputs will be proportional to θ.

The mean d.c. levels are extracted from the limiter outputs by removing the a.c. components in the filter stages 8 and 9 (Fig. 2), and the direct voltages are applied differentially to the recorder 11.

The recorder deflection is then proportional to the phase difference between the two input voltages measured from the datum condition of being in quadrature. As the relationship is linear the magnitude of the datum is of no importance if only phase variations are of interest, and in that case, the recorder can be brought to mid-scale before the anticipated variation occurs by adjustment of the phase-shifter. Further, as the output depends only on the relative phases of the two voltages, the measurement is independent of supply frequency.

Details of one-half of the instrument are shown in Fig. 4. The input signal is applied to the grid of the squaring valve V2 via one-half of the double diode V1. The input is applied via the transformer T1 symmetrically with respect to the cathode potential and at an amplitude of 800 volts (d.a.p.). During the positive half-cycle the valve conducts heavily, the grid being held at cathode potential by the second diode of V1, the first diode

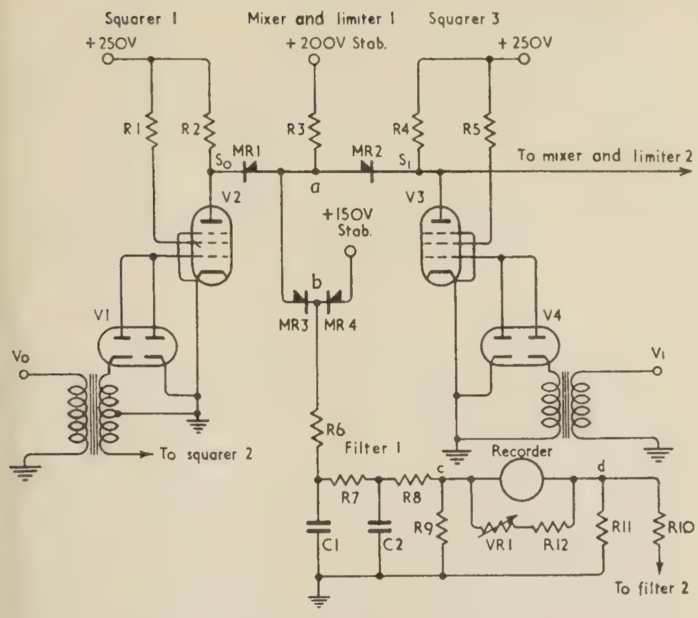


Fig. 4.—Details of squarer, mixer and filter circuits.

R1, R5: 68 kΩ
R2, R3, R4: 22 kΩ
R6: 220 kΩ
R7, R8, R10: 100 kΩ
R9, R11, R12: 220 Ω
C1, C2: 0·5 μF
V1, V4: CV140
V2, V3: CV138
MR1, MR2, MR3, MR4: Q6/5
VR1: 500 Ω

being cut off. During the negative half-cycle the valve is cut off. The anode-voltage waveform is consequently a square wave of about 200 volts amplitude. A second square-wave of the same amplitude appears at the anode of V3, the relative phases being shown in Fig. 3. When both V2 and V3 are cut off the anode voltages rise to +250 volts. The junction *a* of the rectifiers MR1 and MR2 rises to a potential of +200 volts, and these rectifiers cut off. The rectifier MR3 conducts and MR4 is cut off, and point *b* is established at a potential of +200 volts. If either V2 or V3 conducts (say V2, for example) rectifier MR1 will take *a* down to a potential of about 50 volts, MR3 will cut off and point *b* will assume a voltage of +150 volts. The waveform at this point will therefore be a square wave whose mean d.c. level will be dependent on the mark/space ratio. This ratio will in turn depend on the relative phases of the input signals, as shown in Fig. 3. A known fraction of the mean d.c. level at *b* is applied to the recorder by the attenuator formed by R6, R7, R8 and R9. Capacitors C1 and C2 remove the a.c. component from the voltage. The second channel operates in a similar manner with the valve V3 common to the two channels. The direct voltage derived from the second channel corresponding to that at *c* appears at *d*, and the differential voltage between *c* and *d* is applied to the recorder.

The recorder is an electronic servo-driven strip-chart recorder requiring a voltage of 1 mV for full-scale deflection.

(3) SENSITIVITY AND ACCURACY

The full-scale range of $\pm 12\frac{1}{2}°$ of the instrument was determined by the requirements of the particular application in mind when it was developed. For any other application the scale could be expanded or contracted as required by the adjustment of the recorder shunt comprising VR1 and R12. The recorder reading will be linear with phase change for any scale range up to 360°.

The overall accuracy will depend on the following:

(*a*) The sensitivity of the recorder. That used had a dead zone of about $\pm\frac{1}{2}$% full-scale deflection.
(*b*) The overall drift of the instrument for a constant input phase difference.
(*c*) The rate of change of the input phase difference.

With a scale range of 25° the limit of sensitivity of the recorder corresponds to $\pm\frac{1}{8}°$. The long-term overall stability or drift depends primarily on the stability of the 200-volt h.t. supply to the limiters. This is electronically stabilized to a high degree, and tests over several hundred hours showed the stability to be about $\pm\frac{1}{8}°$. The maximum error from these two causes is therefore not likely to exceed $\pm\frac{1}{4}°$.

In recording transients of only several seconds' duration the most important contribution to the error will arise from the transient response of the recorder, and the drift error will be negligible. Tests showed that, with a sinusoidal phase difference between the input signals of 20° (d.a.p.), the overall error was less than $\pm\frac{1}{2}°$ up to a frequency of 1 c/s. Up to 0·5 c/s the overall error was less than $\pm\frac{1}{4}°$. Some improvement in the response to rapid changes of phase could be achieved by using a recorder of faster response, but an upper limit would be set by the necessity of filtering out the a.c. component from the limiters. The minimum tolerable time-constant in the filters is probably five times the period of the supply frequency, i.e. about 0·1 sec, and this would probably limit the frequency of response for conditions as discussed above to about 5 c/s.

(4) EXAMPLES OF RECORDINGS

Two examples of the recordings taken during the Cliff Quay tests are shown in Figs. 5 and 6. Fig. 5 is a recording of the variations in phase of the system busbar caused by pole slipping of the machine on test following a reduction of excitation to the

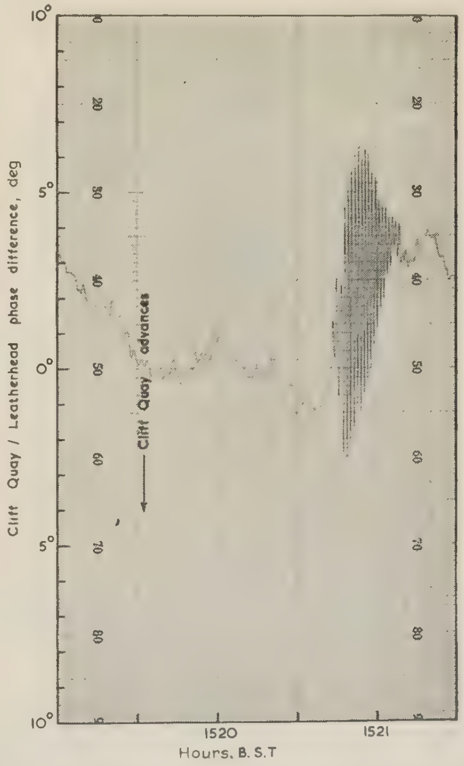


Fig. 5.—Phase variation of system busbar voltage at Cliff Quay during steady-state test.

4th August, 1956.

*

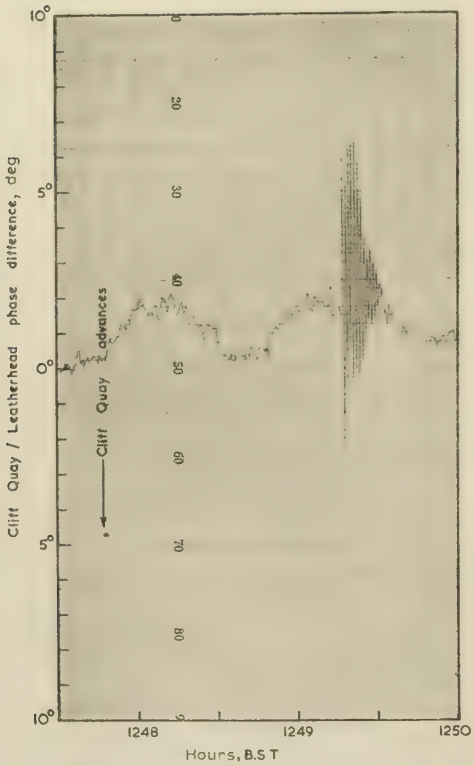


Fig. 6.—Phase variations of system busbar voltage at Cliff Quay following application of 3-phase fault to test busbar.
7th August, 1956.

point where slipping occurs. Fig. 6 shows the phase variations of the system busbar following the application of a 3-phase fault of the test busbar.

Prior to each test the phase-shifter was adjusted if necessary to bring the recorder to mid-scale. This adjustment was necessary, as the absolute phase-difference between Leatherhead and Cliff Quay depended, of course, on the loading conditions on the system between these two points in the network and varied from time to time.

In all, some 20 recordings were made during the Cliff Quay tests, but they are not all reproduced as it is not proposed to discuss them in detail in this paper. In no case did the phase swings reach the amplitude of $\pm 10°$ expected, the greatest peak-to-peak swing recorded being, in fact, 11° at a frequency of about 0·7–0·9 c/s, so that the accuracy assigned to the recordings was $\pm\frac{1}{4}°$.

There were continuous random phase variations between Leatherhead and Cliff Quay in the steady-state conditions as can be seen on the recordings (Figs. 5 and 6). These are genuine variations in phase between the input voltages and are not instrumental effects. Oscillographic tests were made to confirm this point.

It should be noted that, for convenience in reproducing the recordings, only the range $\pm 10°$ has been shown, whereas, in fact, the whole width of the chart corresponds to $\pm 12\frac{1}{2}°$.

(5) COMMUNICATION

The Cliff Quay voltage was transmitted to Leatherhead via a Post Office telephone circuit using an amplitude-modulated carrier at 2·56 kc/s. The modulation depth was about 80% and the transmitted level about 1 mW into 600 ohms. The overall line loss was about 6 dB, and the received signal was amplified before and after demodulation to give a final output at 50 c/s of about 230 volts prior to squaring.

Magneto-telephones were attached to the line via suitable low-pass filters, and ringing was carried out by voice-frequency ringing equipment.

The phase shift of the 50 c/s signal through the communication channel was not known, but in view of the carrier frequency used, it was assumed to be reasonably constant. A change of 10° in the phase delay of the carrier would produce a corresponding change of only 0·2° in the 50 c/s signal, and variations of this degree were not expected.

(6) CONCLUSIONS

A precision voltage-angle recorder has been described which was developed for one particular purpose but has other applications, an example of which is given below. As designed, the instrument has a range of 25° and is suitable for recording phase variations of frequency up to about 1 c/s, but the range can be adjusted to any desired value and the upper frequency limit could be extended if required.

The instrument has since been used at the request of the Southern Electricity Board to record phase differences between two 33 kV supplies at Aldermaston. Alternative 33 kV supplies to the Atomic Weapons Research Establishment are derived from two 132/33 kV substations at Thatcham and Reading which are well separated in the 132 kV system. It was desired to parallel the supplies at Aldermaston on the l.v. side of the 33/11 kV transformers, but difficulty was experienced in doing so. Load flows in the 132 kV system produced a substantial phase difference between Thatcham and Reading, and this, in turn, appeared between the 33 kV supplies at Aldermaston.

The recorder was modified to have a scale of $\pm 25°$, and recordings were taken for a period of a month, during which time the zero and calibration were stable and needed no adjustment. The phase angle between the supplies was found to vary between $+15°$ and $-5°$, and there appeared to be some correlation between the measured phase angle and the loading at Reading generating station.

(7) ACKNOWLEDGMENT

The development of the instrument was carried out at the Central Electricity Research Laboratories, and the paper is published by permission of the Director.

The author would also like to acknowledge the assistance given by members of the Eastern Division of the Central Electricity Authority who arranged and conducted the Cliff Quay tests.

(8) REFERENCES

(1) Busemann, F., and Casson, W.: 'Results of Full-Scale Stability Tests on the British 132 kV Grid System', *Proceedings I.E.E.*, Paper No. 2575 S, February, 1958 (**105** A, p. 347).
(2) Farren, L. I.: 'Phase Detectors—Some Theoretical and Practical Aspects', *Wireless Engineer*, 1946, **23**, p. 330.
(3) Grübel, G.: 'Phase Measuring Instrument for Laboratory and Field Use', *Funk und Ton*, 1949, **3**, p. 315.
(4) Kruse, O. E., and Watson, R. B.: 'An Improved Audio Frequency Phasemeter', *Audio Engineering*, 1950, **34**, p. 9.
(5) Seymour, R. A.: 'A Simple Phase Measuring Circuit', *Post Office Electrical Engineers' Journal*, 1951, **43**, p. 198.
(6) Kritz, J.: 'Precision Phasemeter for Audio Frequencies', *Electronics*, 1950, **23**, No. 10, p. 102.
(7) Yu, Y. P.: 'Zero Intercept Phase Comparison Meter', *ibid.*, 1953, **26**, No. 11, p. 178.

(8) JOHNSON, A. B.: 'A Clipper with Automatic Mark-Space Ratio', *Electronic Engineering*, 1954, **26**, p. 364.
(9) MOSS, F. P.: 'An Audio Frequency Phase-Meter', *ibid.*, 1954, **26**, p. 361.
(10) HALLER, H.: 'A Direct Reading Phasemeter for Frequencies from 50 c/s to 100 kc/s', *Frequenz*, 1954, **8**, p. 325.
(11) SAKURAI, Y., and NAGANO, H.: 'The Magnetic Amplifier as a Phase Detecting Device', *Journal of the Institute of Electrical Engineers of Japan*, 1955, **75**, p. 125.
(12) HOMILIUS, K.: 'Direct Reading Phase Meter for Audio Frequencies using Transistors', *Archiv für Technisches Messen und Industrielle Messtechnik*', 1955, **237**, p. 221.
(13) VANDEN DOOREN, M.: 'A Dynamic Phasemeter', *Revue H.F.*, 1955, **3**, p. 83.
(14) KLASSEN, H., and WENZEL, W.: *Archiv für Technisches Messen und Industrielle Messtechnik*, 1949, **167**, p. T108.
(15) DAVIS, D. L.: 'A Fast Acting Phase-Conscious Indicator', *Electronic Engineering*, 1956, **29**, p. 385.

DISCUSSION ON THE ABOVE THREE PAPERS BEFORE THE JOINT MEETING OF THE MEASUREMENT AND CONTROL SECTION AND THE SUPPLY SECTION, 29TH APRIL, 1958

Dr. P. D. Aylett: I think that the question we should first ask in considering these three papers is, Why do we require to measure the rotor angle?'

There are three reasons. First we may require a rotor-angle indicating instrument in the control room of a power station.

Secondly we may require a rotor-angle signal to control the synchronous machine in some way; e.g. to influence the action of the voltage regulator or the steam valves. It is quite possible that the rotor angle would be required with respect to a point in the power system physically remote from the machine, and techniques described in the paper by Mr. Moran would have to be used.

Lastly there is the need to obtain rotor-angle measurements in order to have a full record of the performance of a machine under test. This requirement has led directly to the work described in these papers, but nevertheless the other uses for rotor-angle signal or indication should be borne in mind.

Mr. Prewett in his paper has indicated that some improvements in his device are necessary. The photo-electric pick-up has its disadvantages, especially for routine use. Some years ago, in the Technical Department of the South Eastern Division of the British Electricity Authority, we constructed a rotor-angle indicator rather similar to the one described in this paper. In this case an electromagnetic pick-up was used. The sensing element consisted of a permanent magnet wound with a coil which was placed close to the shaft of the machine. A very small steel screw was screwed into the shaft, and the projecting head produced in its passage past the sensing element sufficient flux change to induce a substantial voltage in the coil. This pick-up was most successful in operation, and it does not matter, of course, if it gets dirty.

Mr. Moran's paper deals with the interesting topic of long-range rotor-angle measurement, which may become important in the future. It would have been useful if, during the Cliff Quay tests, the rotor angle with respect to a third point in the system, remote from the other two, could have been obtained. The movement of the system during the fault period would then have been known, and the validity of the common assumptions concerning the 'infinite bus' could have been checked.

The films obtained by Messrs. Powell and Harper and shown at the meeting indicate the useful records obtained by this method. This equipment has been used again during recent machine tests, and I have been analysing the results. They are the most accurate and comprehensive obtained from any source.

In conclusion, there is the matter which arises from the measurement of rotor angles and indeed many other quantities during large-scale machine tests. A vast amount of data is recorded in these tests; pages of readings, sheets of oscillograms thousands of feet of film. The time then arrives when all these data have to be analysed. The more accurate and comprehensive the records of the variables, the greater are the difficulties in analysing all the data.

In the future, we shall have to look upon the collection of data in a different way, and I am proposing an ideal solution. I should like to have all the data in digital form and recorded directly on magnetic tape. In the case of the rotor angle, for example, pulses initiated by the shaft of the machine, and the reference voltage, would be recorded directly on to magnetic tape, together with a counting frequency synchronized to the mains supply frequency, thus giving the rotor angle. All data, such as voltages and currents, should be recorded in this way, and a large and fast electronic computer should be used for the task of analysis. Only in this way will the deductions made from the test information match, in some measure, the diligence of those collecting the results.

Mr. R. G. Parr: The display of rotor angle during instability requires clarity, simplicity and ease of comprehension; accuracy is not so important. For this reason I suggest that, if a pen recorder is used, it be given a full 360° coverage without any ambiguity.

A method which we have found very effective is illustrated in Fig. A. The circular trace on the cathode-ray-tube face is

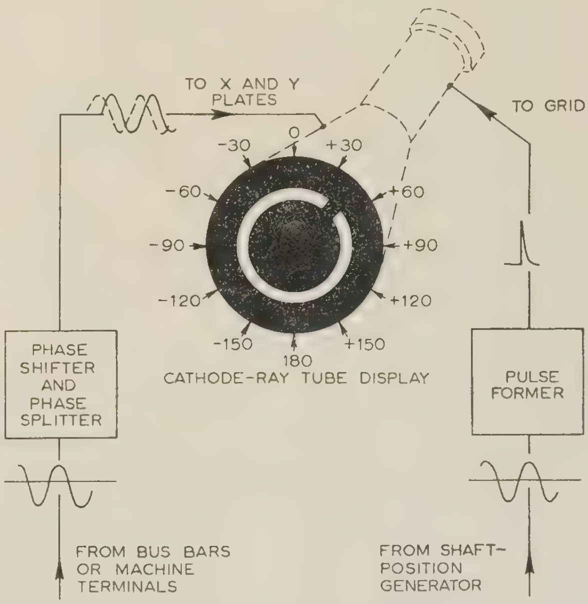


Fig. A.—Rotor-angle display.

formed by the spot travelling round synchronously with the machine or busbar voltage. The blank in the trace is made by a signal derived from the shaft-position generator. The position of the blank indicates the position of the rotor with respect to the machine voltage, i.e. the load angle of the alternator. From such a diagrammatic type of display, it is easy to appreciate the

speed and direction with which a machine is swinging or slipping, and to assess the result of any corrective action.

Finally I would like to comment on some aspects which affect accuracy of measurements using machine or local busbars as a reference. In addition to the difficulty of finding a reference voltage which does not swing in phase when a local machine becomes unstable, it is necessary to be sure, despite the great length of signal leads involved, that no interference is caused by very high currents which may be flowing in adjacent power cables. Finally, Fig. B shows difficulties which may arise owing to distortion of the reference voltage. The considerable harmonic content of a machine voltage for several cycles after a fault is applied and removed can be clearly seen.

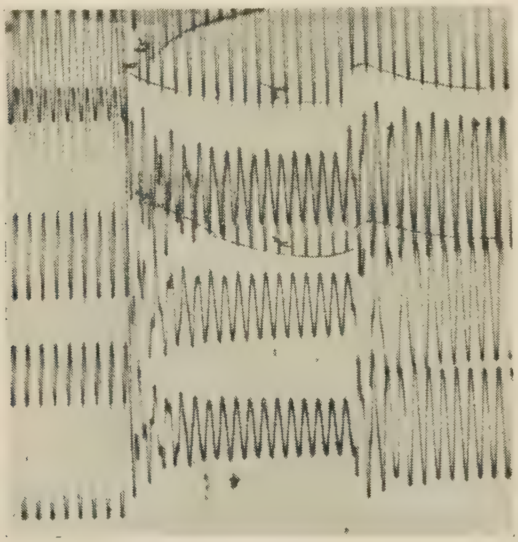


Fig. B

Mr. G. Lyon: The paper by Busemann and Casson (Reference 1 of each paper) presents a vast amount of information, but not by any means all that was made available by the tests. We were promised other papers giving the results obtained by the 'auxiliary teams', dealing with various other measurements. We now have papers presented by three of the teams, which deal excellently with measurement apparatus. But I should have liked them to include—possibly as appendices—rather more information on the results obtained, so that it could be correlated with the earlier papers by the main party.

I should also have liked more information about the records obtained by Mr. Vernon and his colleagues and Prof. H. Davies, and I hope we can still look forward to receiving it.

The purpose of the measurements and the accuracy to be obtained have already been dealt with by Dr. Aylett and Mr. Parr, and I support their views. The assumption that a point such as Leatherhead is an infinite bus seems, from the results, to be sufficiently valid for practical purposes. I suggest that a true infinite bus for the period of the oscillations might be had by reference to a national standard signal of 1 kc/s, such as the French use for load-control purposes. Alternatively would not a crystal-oscillator signal give the constant phase to compare with Leatherhead asked for by Dr. Aylett? Drift effects should be tolerable over the test period of less than one minute.

I suggest that the Masson recorder could display the information for the operator's benefit. I do not think it is as good as Mr. Parr's proposal but it is readily available, and has the features of not running except when it is wanted, while giving a record immediately before and after the disturbance.

I have plotted the accuracy figures given in the paper by Mr. Prewett, and the resulting curve is an odd shape, different in the positive and negative quadrants. The use of all the results obtained would give a more reliable picture of the meter characteristics, and it would be interesting to know whether the analysis has been made. One of the slides used by Mr. Moran did not seem to agree with Fig. 6 of his paper. It showed the results of a worse fault, giving oscillations of up to 11°, whereas both diagrams in the paper show fluctuations of only about 8·5°. I would have appreciated the opportunity of seeing all the results taken by this method, or at least a tabulation of the amplitudes and durations.

Dr. F. H. Last: The stability of generating plant is a very important operational consideration. The three papers describe instruments, each having special applications and limitations. The authors do not overstate their claims for performance and indicate their limitations. The techniques described fall into two categories: local rotor-angle measurement and voltage-displacement measurement between remote points.

The paper by Mr. Prewett describes a tool for the operating engineer, which produces an immediate record of rotor angle with reasonable accuracy. The main value of the recorder is to indicate whether the machine is tending towards or away from stability. If the latter, it tells the operating engineer whether corrective action is having the desired effect.

In my opinion an indicating instrument should also be provided from which the margin can be deduced during stable conditions. There has been difficulty in preventing fouling of the reference point; this appears to have been overcome, and I would like the opportunity of installing a trial unit.

Mr. Powell's instrument achieves a higher accuracy. Its application is not operational but is intended for the analysis of special investigations. The results were of extreme value in the Cliff Quay tests, and the excellent film shown at the meeting, which illustrates rotor movement under stable and unstable conditions, should be produced in an educational form. Technical staff and operating engineers could then be helped to understand more fully the electrical performance of a generator.

I believe that Mr. Moran's instrument has an important operational application. It could be used to give system operating engineers a means of judging transmission-line stability margin, which is particularly important during abnormal feeder-outage conditions.

Will the authors elaborate on what they consider to be other possibilities of their instruments?

Mr. W. T. J. Atkins: With regard to the 'infinite bus' which speakers have mentioned, I would remark that there are radio time and frequency signals of very high accuracy available as a datum both at the points of test and simultaneously at as many other places as may be desired.

Mr. J. E. Price: It is very interesting to have these results presented visually by means of the stroboscope and the cinematograph rather than mathematically. The question is whether we can use this information to prevent instability.

Can we not now go back to the governor end of the set, and apply an epicyclic or differential gear, with one shaft driven by the turbine and one shaft driven by a fractional-horse-power synchronous motor? The movement of the output shaft of the differential gear would give an indication of the phase angles of the alternator rotor and could be applied to bias the governor, by proportional and differential control, in order to prevent the alternator from reaching a position of instability. It could also be used for biasing the automatic voltage regulator to strengthen the alternator field before the alternator reaches the position of instability.

Mr. R. S. Gow (*communicated*): With reference to the paper by Messrs. Powell and Harper, instead of using a ciné camera with all the associated difficulties of synchronizing the illumination and shutter movement, I have used a shutterless camera with constant speed film drive. In fact, this was a standard oscillograph camera and was readily available. A calibrated disc was attached to the alternator shaft and a small part of its periphery was focused on to the centre of the film, the geometry being such that the velocity of the top part of the image relative to the film was zero. The record was therefore clearest at the only point where it had to be read, and the necessity of having a stroboscopic flash equipment of high intensity and short duration was less important. Synchronism with oscillograph records was achieved by fusing small lamps connected in series.

In a later series of tests when a ciné camera was available, this was used for photographing control-room instruments, the shutterless camera being retained for rotor-angle measurement owing to its excellent performance.

THE AUTHORS' REPLIES TO THE ABOVE DISCUSSION

Mr. J. N. Prewett (*in reply*): Dr. Aylett has described a rotor-position pick-up which is simple in principle and satisfactory in use, provided that no objections are raised to drilling a small hole in the rotor shaft. The choice of the pick-up system is determined to a certain extent by the accessibility of the shaft and what attachments are permitted.

Mr. Parr's method of displaying rotor angle has the advantage of 360° coverage without ambiguity, and the display is easy to interpret at a glance. Its application to a permanent installation is not so attractive because of periodic cathode-ray-tube replacement due to spot burn if the trace is bright enough to be seen at a distance over a wide viewing angle, or failure of cathode emission if the beam is cut off except when required for indication.

The use of a Masson recorder to indicate and record rotor angle, suggested by Mr. Lyon, is limited by the small amplitude of the record and the few seconds delay before a record of an event is visible. It might be possible to alter the design to overcome these faults.

In reply to Dr. Last, I feel that the instrument capable of indicating rotor-angle oscillations should be of the recording type, because a clearer indication is given of whether or not stability is being achieved. There are, however, many difficulties in the way of using a recorder in a permanent installation, where it is required to operate at a moment's notice a few times each year. A separate indicating meter calibrated 0–90° can be very useful in checking the machine operating conditions because of the greater ease with which the exact rotor angle may be read.

I agree with Mr. Price that it should be possible to use the rotor-angle information to assist in the automatic control of the generating set. Whether the electro-mechanical system he describes or an electronic method would be the more suitable in a particular application is beyond the scope of this discussion.

In reply to Mr. Lyon, the object of the paper was briefly to describe the equipment used to measure rotor angle rather than to describe the large number of tests and interpret the results. In any case, this would have made the paper unacceptably long. I feel that he is placing undue stress on accuracy in analysing error curves. The instrument was designed to give a qualitative record of rotor angle during periods of instability, while an accurate record which took some time to process was made by stroboscopic and other methods.

Messrs. E. B. Powell and **M. E. Harper** (*in reply*): Both Drs. Aylett and Last refer to the accuracy of the records obtained from our equipment on stability tests. This confirms our claim for the apparatus, which is intended only for use on tests where accuracy is essential.

We have also used the equipment very successfully for determining the stored energy in machines, by photographing the rotor movement when switching out a set carrying about one-tenth of full load. This enables the rotor movement to be accurately measured over the first 10 cycles, during which time the accelerating force, due to no movement of the turbine valves, is constant. The equipment, as Dr. Last mentioned, has also proved of considerable value from an educational angle.

Mr. Parr's method of showing the rotor movement on a cathode-ray tube is of interest. This would provide the same facilities as ours for visually observing the slow movement of the rotor during certain tests, and it has the advantage that the information can be provided at several points. It is, however, difficult to photograph this cathode-ray image and obtain a permanent record. It was found during transient tests that the recording of the results is essential, since the movement of the rotor is so rapid one cannot say what exactly has happened.

The distortion of the reference voltage under short-circuit conditions, referred to by Mr. Parr, will never be as great as that shown in Fig. B, provided that the reference busbar approaches infinite busbar conditions. The distortion of the wave in Fig. B, which is considerable, disappears for all practical purposes in 4–5 cycles. We have found from tests that an initial error of $\pm 3°$ may occur due to distortion, but will be eliminated in $0 \cdot 1$ sec. Any error after the fault is cleared can be ignored, since the rotor angle is then large compared with $\pm 3°$.

Messrs. Lyon and Atkins both refer to the difficulty of obtaining an infinite busbar as reference and suggest that a standard base uninfluenced by the system be used. We consider that this is difficult to adopt in practice. We carried out tests on a set using a local oscillator to provide a stable base reference for the stroboscopic flash equipment and found it was impossible to hold the stroboscopic image stationary under constant load conditions for more than a second or two. The system frequency is continually changing slightly and 2° movement of the shaft per second relative to the base reference will occur for a frequency change of $0 \cdot 0055$ c/s. In our view, the fact that the reference busbar was probably varying by $\pm 5°$, as shown by Mr. Moran's tests, is not a serious matter.

Mr. Price's suggestion that the stable operation of machines could be ensured by installing special governing gear which would be biased by the rotor angle is interesting. This could easily be done if the use of the ordinary centrifugal governor, which is now no longer justified on constant-speed systems, were abandoned. It would be a simple matter to equip the electrical-hydraulic type governor gear, which is now being installed in a number of countries in place of the centrifugal governor, with a rotor-angle biasing feature.

Mr. Gow's suggestion that a shutterless camera, such as is used for oscillograph work, could with advantage be used instead of a ciné camera, was initially considered. It was decided, however, that the screening of a shutterless camera from the effect of outside light would have been very difficult, as the camera had to be used for photographing not only the disc on the end of the shaft but in some cases a scaled tape fastened round the shaft of the machine. In the latter case, the situation of the tape was frequently inaccessible to a shutterless camera unless it was of special design. A ciné camera for 100 ft of film was already available, and its adoption for use with the stroboscopic equipment was more economical than the purchase of a shutterless camera.

Mr. F. Moran (*in reply*): Dr. Aylett mentions the possible

requirement of controlling the rotor angle of a synchronous machine with respect to a point in the power system remote from the machine. This would appear to be an attractive approach to the stability problem in the case of machines feeding the system over long transmission lines. This solution poses a problem in communication which would have to be solved in a reliable way, but if automatic frequency control were in use, the same communication channel could no doubt be utilized to carry the control instructions for both the active and reactive power outputs of the machine. It should be noted that, in the tests described in the paper, only the variations in phase between the two remote points were of interest as opposed to the absolute value of the phase difference. However, no doubt similar techniques could be used for the latter measurement with some refinement for indicating a datum.

With regard to the proposal made by Dr. Aylett for recording data in digital form and processing it in a computer, this approach has great possibilities, and is, in fact, used, notably in the guided-weapons field. However, care should be taken that the scientist does not lose touch with the problem, as it is frequently the anomalies in the results and recordings which point the way to new knowledge, and these can easily be overlooked in automatic data processing.

Both Dr. Aylett and Mr. Lyon comment on the assumption that Leatherhead could really be regarded as an infinite busbar. Whilst I agree that a measurement at a third point might be interesting in any future tests, I feel that, within the limits of measurement, the assumption with regard to Leatherhead was valid. The proposal by Mr. Lyon for comparing the Leatherhead voltage with a standard 1 kc/s signal or crystal oscillator does not appear to be a satisfactory solution. The system as a whole is constantly subjected to random load fluctuations which result in continuous random frequency fluctuations. The proposed measurement would simply reflect these frequency fluctuations integrated with respect to time.

Mr. Atkins also notes that radio time and frequency signals were available at the point of test and at as many other places as desired. These could presumably have been utilized by making simultaneous phase recordings at the test and remote points with respect to such a datum and subsequently extracting the desired phase variations as the difference between the pair of recordings so obtained. This would appear to introduce serious problems in the accuracy and synchronization of the recordings, the only benefit being the lack of need of a communication channel.

In reply to Mr. Lyon, it was not possible to include in a short paper all the test results. The recording shown in Fig. 6 was not suitable for the preparation of a slide. The slide showed only a typical result, which it was not my intention to discuss in detail.

The proposal for using the intrument in an operational role, as mentioned by Dr. Last, had not been considered but would be an interesting application.

621.315.61 : 621.317.32

The Institution of Electrical Engineers
Paper No. 2730 M
Dec. 1958
©

THE SELF-EXTINCTION OF GASEOUS DISCHARGES IN CAVITIES IN DIELECTRICS

By E. C. ROGERS, B.Sc., Graduate.

(*The paper was first received* 4*th June, and in revised form* 18*th July*, 1958.)

SUMMARY

The paper describes investigations of the variations of discharge-extinction voltage which occur when a dielectric sample containing a single air-filled cavity is subjected to a 50 c/s testing voltage greater than that required to initiate discharges in the cavity. A particular aim of this work was to determine the causes of the phenomenon of self-extinction, whereby, under certain conditions, such discharges may spontaneously extinguish, even though the voltage applied to the sample may be several times the initial discharge-inception value. Automatic test equipment was used to measure and record the discharge-extinction voltages of samples under test at regular intervals, so permitting the uninterrupted study of the variations over long periods.

The majority of the tests were made on polythene samples, but self-extinction of discharges has been observed with cavities in a number of other dielectrics. The conditions under which discharges in cavities spontaneously extinguish are described, and it is shown that the effect may be attributed to an increase in the conductivity of the cavity walls, induced by the discharges themselves.

(1) INTRODUCTION

Progressive deterioration caused by discharges in gas-filled cavities has long been known to be one of the major factors limiting the life of cable and capacitor dielectrics subjected to power-frequency stresses. The conditions for the onset of these discharges are now well established,[1] and it has been shown that over a wide range of cavity depths and gas pressures the voltage required across a cavity to initiate discharges is independent of the nature of the bounding dielectric and conforms with Paschen's law, so that the basic mechanisms of gaseous breakdown between dielectric surfaces are probably the same as in breakdown between metal electrodes.

Comparatively little is known, however, of the complex chemical and physical processes which take place in a cavity in a dielectric sample when a 50 c/s voltage greater than the initial discharge-inception value is maintained across it. Under these conditions, transient discharges occur in each half-cycle of the applied voltage and increase in number with increasing voltage.[2] With cavities in many commonly used dielectrics, e.g. polythene, polyvinyl chloride and rubber, substantial variations of the discharge-extinction voltage are frequently observed, and if the extinction voltage increases sufficiently the discharges sometimes spontaneously extinguish, even though the applied voltage may be several times the initial discharge-inception value. The paper describes experimental work that has been carried out to determine the nature and causes of this phenomenon, which is termed 'self-extinction'. Although the phenomenon has been observed by a number of workers,[1, 2, 3] it is believed that no systematic investigations have been previously described, and the work is therefore put forward as an original contribution to the understanding of the fundamental behaviour of gaseous discharges in cavities in dielectrics.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
The author is with British Insulated Callender's Cables Ltd.
The paper is based on an M.Sc. dissertation which is shortly to be submitted to the University of Bristol.

(2) EXPERIMENTAL WORK

(2.1) Method

The method of studying the effect has been to apply to a dielectric sample containing a single air-filled cavity a constant 50 c/s testing voltage, V_T, greater than the initial inception voltage, so that, initially at least, multiple discharges occur in each half-cycle. Then, at intervals of 5 min, the discharge-extinction voltage, V_e, is measured by rapidly decreasing the applied voltage until discharges cease, and immediately returning it to the test value. Successive values of V_e, obtained in this way, are plotted against time, thus giving the 'extinction-voltage/time curve' of the sample. A servo mechanism was developed[4] for carrying out this procedure entirely automatically; by its use the variations of extinction voltage of a sample can be followed over periods of days or weeks as required.

Although, as a matter of experimental convenience, it is the variations of discharge-extinction voltage that are studied, the discharge-inception voltage would be expected to show a similar variation. The inception voltage is, of course, always greater than the extinction voltage, usually by about 10%.[1]

(2.2) The Samples

For tests with internal cavities, samples were made of three sheets of dielectric placed face to face, the middle sheet being cleanly punched at its centre with a circular hole, as shown in Fig. 1. For tests with electrode-adjacent cavities, the samples consisted of two dielectric sheets, the lower one being punched. Some tests were also made on single sheets of dielectric with a cylindrical electrode-adjacent cavity moulded in one face. The sheets were selected to be free from defects and were carefully degreased by cleaning with alcohol.

(2.3) The Electrode System

The principal requirement of the electrode system is that it shall be completely discharge-free at the test voltage. A number of systems were tried during the course of the work, but most of the tests to be described were made with system A (Fig. 1). With this system, the sample is mounted between an upper cylindrical brass electrode of 1½ in diameter, with radiused edges, and a lower 4 in square brass plane electrode. Intimate electrode-dielectric contact is ensured by silver sub-electrodes of ¾ in and 2 in diameter deposited by vacuum evaporation on to the outer faces of the upper and lower sheets of the sample prior to assembly. In tests with electrode-adjacent cavities, the lower silver electrode is omitted, and a sheet of copper foil is placed between the underside of the sample, which contains the cavity, and the lower brass plane. The upper brass electrode is surrounded by a hollow Tufnol cylinder which is cemented to the upper face of the sample, and filled with molten degassed petroleum jelly, which, when solidified, prevents discharges at the edges of the electrode. Tests with blank samples, i.e. samples containing no cavity, have shown this type of electrode system to be discharge-free for stresses of at least 100 kV/cm.

Some of the later tests were made with system B (Fig. 1), which permits the use of higher testing stresses and is easier to

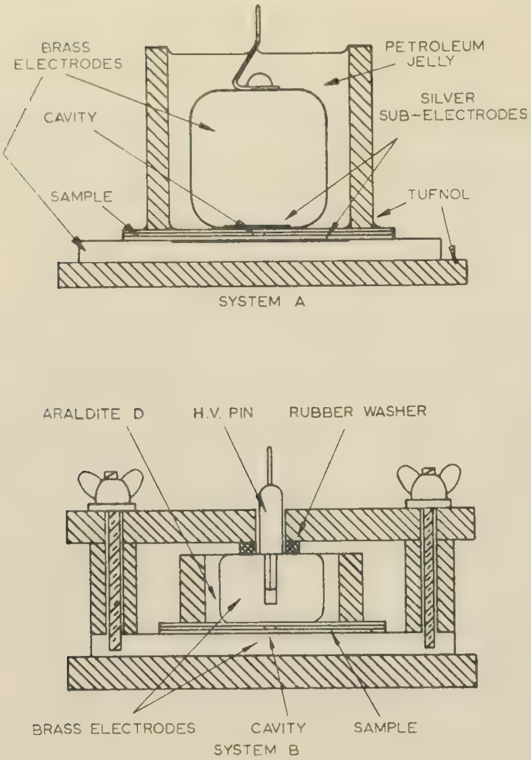


Fig. 1.—Sample construction and electrode systems.

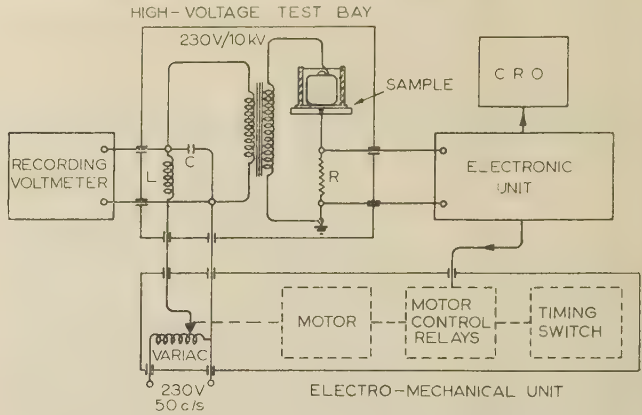


Fig. 2.—Block diagram of the servo mechanism.

assemble. The upper electrode is demountable, since Araldite D is used instead of petroleum jelly as the discharge-suppression medium, and discharges between electrodes and sample are prevented by thin films of silicone fluid. This system can be made discharge-free for stresses up to 400 kV/cm.

(2.4) The Detection of Discharges

The test circuit is shown in Fig. 2. The upper brass electrode is connected to the h.v. terminal of a 10 kV discharge-free test transformer, and the lower electrode is returned to the earthed end of the secondary through the 100-kilohm resistor R. Discharges in the sample cause current pulses in the circuit, and the resulting voltage pulses developed across the resistor may be amplified and displayed on an oscilloscope. The 50 c/s voltage component which also appears across the resistor is suppressed by a simple high-pass filter.

The primary winding of the transformer is fed from a Variac. High-frequency mains interference is rejected by the low-pass filter made up of the air-core choke L and the discharge-free capacitor C.

(2.5) The Servo Mechanism

A full description of the servo mechanism has been given elsewhere,[4] and only a brief outline of the mode of operation will be given here. The system, which is shown in schematic form in Fig. 2, consists of two units:

(i) The electronic unit, which senses the presence, or absence, of discharges within the sample.
(ii) The electro-mechanical unit, which is basically a motor-driven Variac supplying the input voltage to the test transformer, and so controlling the voltage applied to the sample.

The voltage applied to the sample is normally constant at the test value, V_T. At intervals of 5 min, determined by the timing switch, the voltage is automatically reduced until extinction of discharges occurs, and is then returned to the test value. The primary voltage of the test transformer is continuously recorded, so that values of the discharge-extinction voltage are plotted as the extremities of a series of downward-going spikes on the recorder chart. Typical examples of automatically plotted extinction-voltage/time curves are given in Fig. 3.

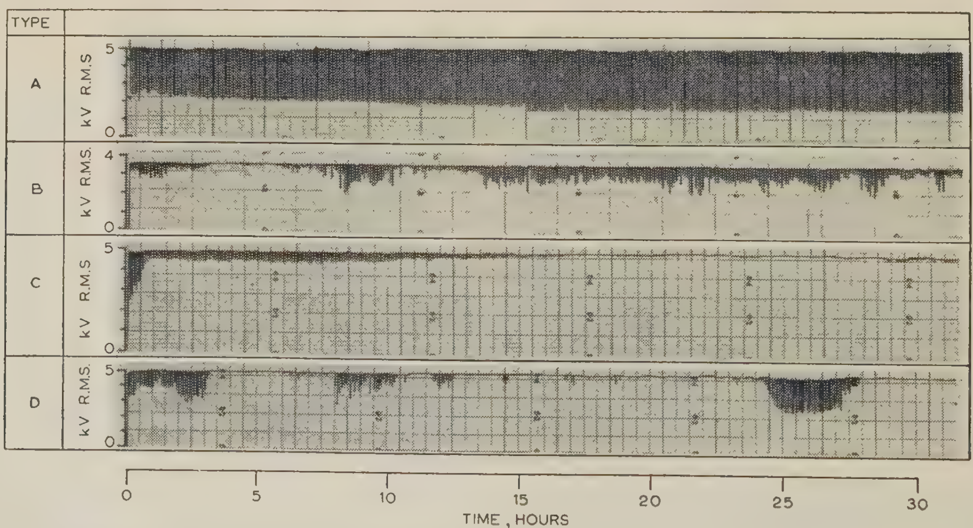


Fig. 3.—Examples of the four characteristic types of extinction-voltage/time curve obtained with polythene samples.

The extinction of discharges, as the applied voltage is slowly reduced, is usually an intermittent process rather than a sudden cessation, and the extinction voltage is taken as the voltage at the time when pulses have been absent for about ½ sec.

In order to minimize interference with the discharge sequence, it is desirable to measure V_e as rapidly as possible. However, to minimize overshoot due to the inertia of the mechanical system, a slow approach to V_e is also desirable. To meet these conflicting requirements the servo mechanism operates at two speeds. The voltage is reduced from the test value, V_T, at high speed (200 volts/sec on the sample) until discharges become intermittent, indicating that extinction is imminent. The extinction voltage, V_e, is then approached at slow speed (50 volts/sec) and, on cessation of discharges, the voltage is returned to the test value at high speed.

The amplitude of the smallest pulse across resistor R to which the servo mechanism responds is about 6 mV, which corresponds to a discharge of approximately 1 pC. This sensitivity was more than adequate, since, with samples of the type tested, the pulse amplitude was usually of the order of 100 mV or greater.

(2.6) 1 000 c/s Voltage Supply

With some of the samples, measurements of the discharge-inception voltage at 1 000 c/s were made before and after carrying out the extinction-voltage/time tests at 50 c/s. The equipment for these measurements consisted of an *RC* oscillator feeding a buffer amplifier, the output of which was taken via a phase-splitting transformer to a push-pull output stage. The output voltage was applied to the primary winding of a transformer giving a maximum secondary voltage of 5 kV. The method of discharge detection was the same as that used at 50 c/s and described in Section 2.4.

(3) RESULTS OF EXTINCTION-VOLTAGE/TIME TESTS ON POLYTHENE SAMPLES

(3.1) Types of Polythene Used

The samples used were made from the following three types of polythene sheet:

(*a*) Sheets, with a good surface, prepared by compression moulding from chips of grade 2 polythene.

(*b*) Commercially obtained sheets of grade 7 polythene, also with a good surface.

(*c*) Commercially obtained sheets of grade 20 polythene, with a slightly abraded surface.

(3.2) Characteristic Types of Extinction-Voltage/Time Curve

The following method of assessing and presenting the results has been adopted. First, all those tests in which any doubt as to the authenticity of the result existed, e.g. because the cavity had collapsed, evidence of external discharges was found, mains failure occurred, or malfunctioning of the test equipment was suspected, were discarded. After this preliminary elimination, the number of valid extinction-voltage/time curves was far too great to permit of individual reproduction. Fortunately, however, though there are frequently considerable differences in the detailed behaviour of apparently identical samples tested under the same conditions, it was found possible to classify the curves qualitatively into four basic types, so permitting a tabular form of presentation. The four types, typical examples of which are given in Fig. 3, have the following characteristics:

Type A.—The extinction voltage, V_e, remains substantially constant at about the initial value.

Type B.—V_e fluctuates considerably, but though it may rise well above the initial value, it does not reach the test voltage, V_T, except, perhaps, for very short periods, and so discharges are only extinguished occasionally, if at all.

Type C.—V_e rises to V_T during the first few hours, and subsequently remains just below, or actually greater than, this value. Discharges are therefore intermittent, or extinguished.

Type D.—As with type C, V_e rises to V_T during the first few hours. Subsequent descents of V_e occur, however, so that the discharges are only periodically extinguished or intermittent.

(3.3) Polythene Samples with Internal Cavities

(3.3.1) Effect of Cavity Diameter.

The results given in Table 1 show that, when samples of grade 2 polythene containing internal cavities with a range of diameters were tested at voltages of about twice the initial inception value, the same type of V_e/time relationship was obtained with all cavity diameters; and with all samples except No. 24, V_e tended

Table 1

EFFECT OF CAVITY DIAMETER ON V_e/TIME RELATIONSHIP OF POLYTHENE SAMPLES CONTAINING INTERNAL CAVITIES

Type of polythene	Sample Nos.	Cavity dimensions		d/m	Test conditions			Mean initial V_i	Types of V_e/ time curve
		Depth m	Diameter d		Voltage	Stress*	Duration		
		cm	cm		kV	kV/cm	h	kV	
G2	22, 37	0·075	0·16	2·1	9	50	100	5·4	C C
	33, 34		0·32	4·3				4·0	C C
	23, 24		0·48	6·4				4·3	C B
	25, 26		0·64	8·5				3·7	C C
G7	190, 191	0·025	0·16	6·4	5	67	30	2·4	C C
	192, 193								C C
	213, 214								D D
	216, 217	0·025	0·32	12·8	5	67	30	2·0	B A
	218, 219								A A
	220, 221								A A
G20	116, 119, 120	0·030	0·16	5·3	5	56	130	2·9	C C C
	107, 108, 115	0·030	0·40	13·3	5	56	130	2·4	C C C
	259, 260	0·040	0·64	16·0	6·6	52	48	2·7	D C

* The stress is equal to the test voltage divided by the total sample thickness.

to rise to V_T at the start of the test. In the cavities of smaller diameter the discharges became extinguished or very intermittent, whereas with the larger-diameter cavities V_e rose almost to V_T and then remained just below this level, so that discharges, though sometimes intermittent, were rarely extinguished. Samples of grade 20 polythene behaved similarly, except that, with sample No. 259, fluctuations of V_e occurred after the initial rise to V_T. With samples of grade 7 polythene, however, the type of V_e/time relationship obtained was diameter-dependent, and with the larger-diameter cavities V_e remained substantially constant at the initial value.

The increase of initial discharge-inception voltage with decreasing cavity diameter is to be expected from considerations of the stress distribution in the samples.[1]

(3.3.2) **Effect of Cavity Depth.**

The results given in Table 2 show that, when samples of grade 2 polythene containing internal cavities of 0·025 and 0·075 cm depth were tested at voltages of about twice the initial discharge-inception value, the same type of V_e/time relationship was obtained with both depths. With all the samples except No. 24, V_e rose to V_T in the first few hours, and in the cavities with the smaller diameter/depth ratios, discharges were extinguished or intermittent for the greater part of the test.

(3.3.3) **Effect of Test Voltage.**

The results given in Table 3 show that, when samples of grade 20 polythene containing internal cavities of two different diameters were tested at voltages of about two and four times the initial discharge-inception value, the same type of V_e/time relationship was obtained at both test voltages and with both cavity diameters. With all the samples, discharges were extinguished or intermittent after the first few hours and remained so for the duration of the test, except with sample No. 111. With this sample, a number of sudden but temporary descents of V_e were recorded.

(3.3.4) **Effect of Resting.**

It has been shown that, when samples of grade 2 and grade 20 polythene containing internal cavities are subjected to test voltages greater than the initial discharge-inception value, V_e tends to rise to V_T; moreover, within the limits considered, this effect is independent of the depth and diameter of the cavity, and of V_T. In order to determine whether the increases of extinction and inception voltages were permanent, tests on a number of the samples were repeated after a period of rest; the results are given in Table 4. With all the samples, the inception voltages had recovered almost to the original value after resting, and, with the exception of one sample, the same type of V_e/time

Table 2

Effect of Cavity Depth on V_e/Time Relationship of Polythene Samples containing Internal Cavities

Type of polythene	Sample Nos.	Cavity dimensions: Depth m	Cavity dimensions: Diameter d	d/m	Test conditions: Voltage	Test conditions: Stress*	Test conditions: Duration	Mean initial V_i	Types of V_e/time curve
		cm	cm		kV	kV/cm	h	kV	
G2	23, 24	0·075	0·48	6·4	9	50	50	4·3	C, B
	31, 32	0·025	0·48	19·2				4·2	C, C
	25, 26	0·075	0·64	8·5	9	50	50	4·1	C, C
	35, 36	0·025	0·64	25·6				4·5	C, C

* The stress is equal to the test voltage divided by the total sample thickness.

Table 3

Effect of Different Test Voltages on V_e/Time Relationship of Polythene Samples containing Internal Cavities

Type of polythene	Sample Nos.	Cavity dimensions: Depth m	Cavity dimensions: Diameter d	d/m	Test conditions: Voltage	Test conditions: Stress*	Test conditions: Duration	Mean initial V_i	Types of V_e/time curve
		cm	cm		kV	kV/cm	h	kV	
G20	116								C
	119	0·030	0·16	5·3				2·9	C
	120				5·0	56	130		C
	107								C
	108	0·030	0·40	13·3				2·4	C
	115								C
G20	111								D
	112	0·030	0·16	5·3				3·2	C
	114				10·0	112	130		C
	105	0·030	0·40	13·3				2·6	C
	118								C

* The stress is equal to the test voltage divided by the total sample thickness.

Table 4

RESULTS OF REPEATED V_e/TIME TESTS ON POLYTHENE SAMPLES CONTAINING INTERNAL CAVITIES

Type of sample and test conditions	Sample No.	No. of test	Initial V_t	Test period	Rest period	Type of V_e/time curve
			kV	h	h	
G2 Polythene	27	1	5·4	100	570	C
m, 0·050 cm		2	4·7	100		C
d, 0·16 cm						
V_T, 9 kV	28	1	3·9	100	570	C
Stress, 50 kV/cm*		2	4·8	100		C
	29	1	4·7	110	450	C
		2	4·2	100		C
	30	1	3·9	110	450	C
		2	3·5	100		D
G20 Polythene	107	1	2·5	166	193	C
m, 0·030 cm		2	2·5	26		C
d, 0·40 cm						
V_T, 5 kV	108	1	2·3	166	193	C
Stress, 56 kV/cm*		2	2·2	26		C

* The stress is equal to the test voltage divided by the total sample thickness.

curve was obtained in the second test as in the first. The initial rate of increase of V_e was usually more rapid in the second test.

With those samples of grade 7 polythene that exhibited self-extinction, it was again found that the increases of V_e were temporary only, and recovery to the initial value was complete after a rest of 18 h. The self-extinction of discharges in polythene samples containing internal cavities is therefore a temporary, but repeatable, effect.

(3.4) Polythene Samples with Cavities adjacent to a Copper Electrode

(3.4.1) Effect of Cavity Diameter.

Table 5 shows the results of V_e/time tests on polythene samples containing cavities, with a range of diameters, adjacent to a copper electrode. Samples of grade 2 and grade 20 polythene, having cavities of similar depth and tested under similar conditions, showed the same pattern of behaviour. With the cavities of the two smallest diameters (0·16 and 0·32 cm), discharges became extinguished or intermittent in the first few hours, and V_e/time curves of type C or D were obtained. With cavities of the next largest diameter (0·48 cm) the extinction voltages fluctuated, but the discharges were not extinguished, and type B curves were obtained. Finally, with cavities of the largest diameter (0·64 cm) there was little variation of V_e throughout the test, and type A curves were obtained. The results for the grade 7 polythene samples are less consistent, but nevertheless there is clearly a tendency for self-extinction to be more probable in the cavities with the smaller diameters.

(3.4.2) Effects of Testing Voltage and of Resting.

In Section 3.4.1 it was shown that, when samples of grade 20 polythene containing cavities adjacent to a copper electrode, and of small diameter/depth ratio, are tested at voltages of about twice the initial inception value, V_e rises to V_T and discharges

Table 5

EFFECT OF CAVITY DIAMETER ON V_e/TIME RELATIONSHIP OF POLYTHENE SAMPLES CONTAINING CAVITIES ADJACENT TO A COPPER ELECTRODE

Type of polythene	Sample Nos.	Cavity dimensions: Depth m	Cavity dimensions: Diameter d	d/m	Test conditions: Voltage	Test conditions: Stress*	Test conditions: Duration	Mean initial V_t	Types of V_e/time curve
		cm	cm		kV	kV/cm	h	kV	
G2	92, 93	0·050	0·16	3·2	4·5	45	100	3·4	D, D
	70, 71		0·32	6·4				3·0	C, D
	94, 95		0·48	9·6				2·6	B, B
	72, 73		0·64	12·8				2·4	A, A
G7	204–7	0·025	0·16	6·4	5	67	70	2·5	D, D, D, A
	236–9								C, D, C, D
	224–8	0·025	0·32	12·8	5	67	70	2·4	D, B, A, A
	229–31								A, D, A
G20	262, 263	0·048	0·16	3·3	5·2	54	65	2·8	D, C
	81	0·045	0·16	3·6	4	44	100	1·6	C
	83, 101	0·045	0·32	7·1	4	44	100	2·5	C, D, D
	102								
	86, 87	0·045	0·48	10·6	4	44	100	2·6	B, B
	88, 89		0·64	14·2				2·4	A, A

* The stress is equal to the test voltage divided by the total sample thickness.

Table 6

RESULTS OF REPEATED V_e/TIME TESTS AT DIFFERENT VOLTAGES ON POLYTHENE SAMPLES CONTAINING CAVITIES ADJACENT TO A COPPER ELECTRODE

Type of sample	Sample No.	Test No.	Test conditions				Initial V_i	Type of V_e/time curve
			Voltage	*Stress	Test period	Rest period		
			kV	kV/cm	h	h	kV	
G20 Polythene	262	1	5·2	54	65	24	2·8	D
m, 0·048 cm		2			24		2·5	D
d, 0·16 cm	263	1			65	24	2·8	C
		2			24		2·0	C
G20 Polythene with	158	1	5·3	150	170	90	1·9	B
moulded cavities		2	5·3	150	54		3·2	B/C
m, 0·015 cm	159	1	5·3	150	170	90	2·6	C
d, 0·16 cm		2	5·1	145	54		3·4	C
	160	1	8·8	250	170	90	2·6	C
		2	8·8	250	50		3·4	C
	161	1	8·8	250	0·25	—	2·1	—

* The stress is equal to the test voltage divided by the total sample thickness.

Table 7

EFFECT OF CAVITY DIAMETER ON V_e/TIME RELATIONSHIP OF POLYTHENE SAMPLES CONTAINING CAVITIES ADJACENT TO A PLATINUM ELECTRODE

Type of polythene	Sample No.	Cavity dimensions		d/m	Test conditions			Initial V_i	Types of V_e/time curve
		Depth m	Diameter d		Voltage	Stress*	Duration		
		cm	cm		kV	kV/cm	h	kV	
G20	264	0·044	0·16	3·6	4·9	58	65	2·4	C
	267	0·048	0·16	3·3	5·0	52	48	2·8	C
	251	0·042	0·32	7·6	4·8	57	48	2·0	B
	261	0·040	0·64	16·0	4·8	57	48	1·7	B
	265	0·048	0·64	13·3	4·9	51	45	2·3	A

* The stress is equal to the testing voltage divided by the total sample thickness.

are extinguished or become intermittent. In order to determine the permanence of this effect, samples Nos. 262 and 263 were tested again after being rested for 24 h. The results, given in Table 6, show that after this time the V_e's had fallen again and were actually less than the original values. Also, in the second tests, the same types of V_e/time curves were obtained as in the first tests.

Table 6 shows, in addition, the results of tests at two voltages on samples of grade 20 polythene containing moulded cavities adjacent to a copper electrode. Sample 161, tested at 250 kV/cm, broke down through the edge of the cavity after only 15 min. Sample 160, however, withstood the same stress for 170 h, and discharges were extinguished after the first few hours. Sample 159, tested at 150 kV/cm, gave a similar result, but sample 158, also tested at this stress, showed type B behaviour, and though considerable variations of V_e were recorded, discharges were never extinguished.

After 90 h resting the inception voltages of the samples had recovered almost to the original values. The tests were then repeated, and with samples 159 and 160, type C curves were again obtained. With sample 158, the behaviour in the second test differed from that of the first in that discharges were extinguished during the last 8 h.

These results show that, as with internal cavities, the self-extinction of gaseous discharges in polythene samples containing cavities adjacent to a copper electrode is a temporary, but repeatable, effect.

(3.5) Polythene Samples with Cavities adjacent to a Platinum Electrode

Table 7 shows the results of V_e/time tests on polythene samples containing cavities adjacent to a platinum electrode. As with cavities adjacent to a copper electrode (Section 3.4.1), V_e tends to increase to V_T only with the cavities of smaller diameter. With these samples (264 and 267), however, discharges were not actually extinguished, except perhaps for very short periods, and for the greater part of the test V_e remained just below V_T.

(4) TESTS ON OTHER DIELECTRICS

In tests made on polyvinyl-choride samples containing internal cavities of small diameter/depth ratio, discharges were extinguished even with test voltages of five times the initial inception value. The V_e/time curves obtained differed from those for polythene in that the rise of V_e to V_T was frequently preceded by a flat portion in which V_e remained constant at about the initial value for a few hours. With samples containing cavities of large diameter/depth ratio, however, the discharges did not extinguish, and V_e remained substantially constant throughout the test.

Rubber samples, containing moulded electrode-adjacent cavities, and tested with voltages of about $1\frac{1}{2}$ times the initial inception value, also showed the self-extinction effect, and type D curves were obtained, i.e. V_e rose to V_T but periodically descended again.

With both these materials, self-extinction was found to be a temporary effect, and after a period of rest the V_e's tended to recover to their initial value.

(5) OBSERVATION OF THE DISCHARGE PULSES

The servo mechanism ceases to respond to discharges when either the pulse amplitude falls below the limit of sensitivity or the mean pulse-recurrence time becomes greater than about $\frac{1}{2}$ sec, i.e. the cavity discharges, on the average, less than once in 25 cycles. With each test an oscilloscope was used to make periodic observations of the discharge pulses, and in those tests in which discharges became extinguished, the pulse amplitude remained above the limit of sensitivity but the pulses became increasingly intermittent. During the periods of apparent extinction, bursts of discharges sometimes occurred at intervals of a few seconds or minutes, the duration of each burst being too short to operate the servo mechanism. Very intermittent single pulses were also sometimes detected. It therefore seems that self-extinction should be regarded as a condition of extreme intermittency, rather than of total extinction.

In the tests with electrode-adjacent cavities, where the type of V_e/time curve obtained was markedly dependent on cavity diameter, the sequence of discharges in the smaller-diameter cavities, before self-extinction occurred, was frequently unstable and the epoch and amplitude of the discharge pulses, and the number per cycle, changed rapidly from minute to minute. In the tests with large-diameter cavities, however, in which discharges were not extinguished, the discharge sequence remained comparatively stable.

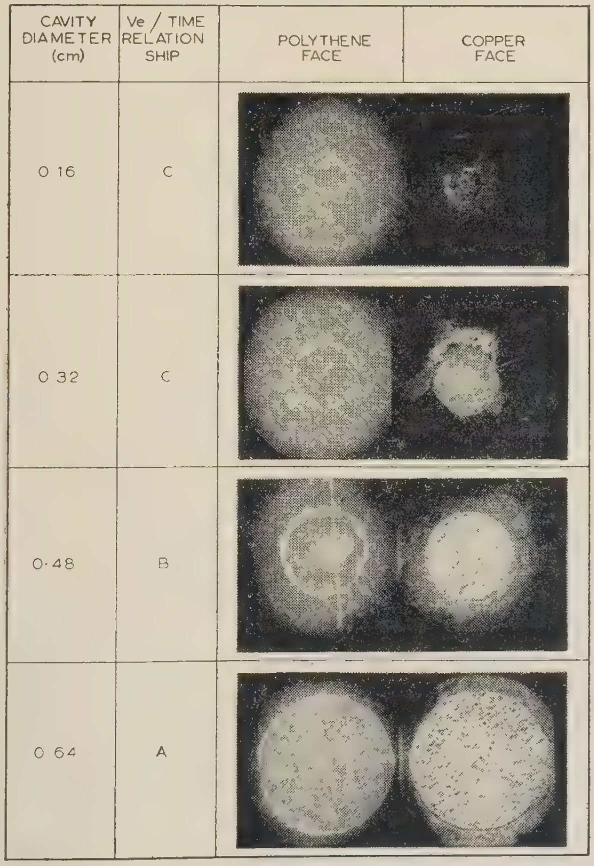


Fig. 4.—Discharge damage in grade 20 polythene samples containing cavities adjacent to a copper electrode and tested at a voltage of about twice the initial inception value.

Cavity depth, m, 0·045 cm.
Duration of test, 100 hours.

(6) MICROSCOPIC EXAMINATION AFTER TESTING

(6.1) Polythene Samples with Cavities adjacent to a Copper Electrode

After testing, the samples were dismantled and the cavity faces examined under a binocular microscope for signs of discharge damage. With samples of all three types of polythene, the nature and extent of the damage was markedly dependent on the diameter of the cavity. This is illustrated in Fig. 4, which shows the polythene and copper faces of electrode-adjacent cavities in grade 20 polythene samples that were tested for 100 h at a voltage of about twice the initial discharge-inception value.

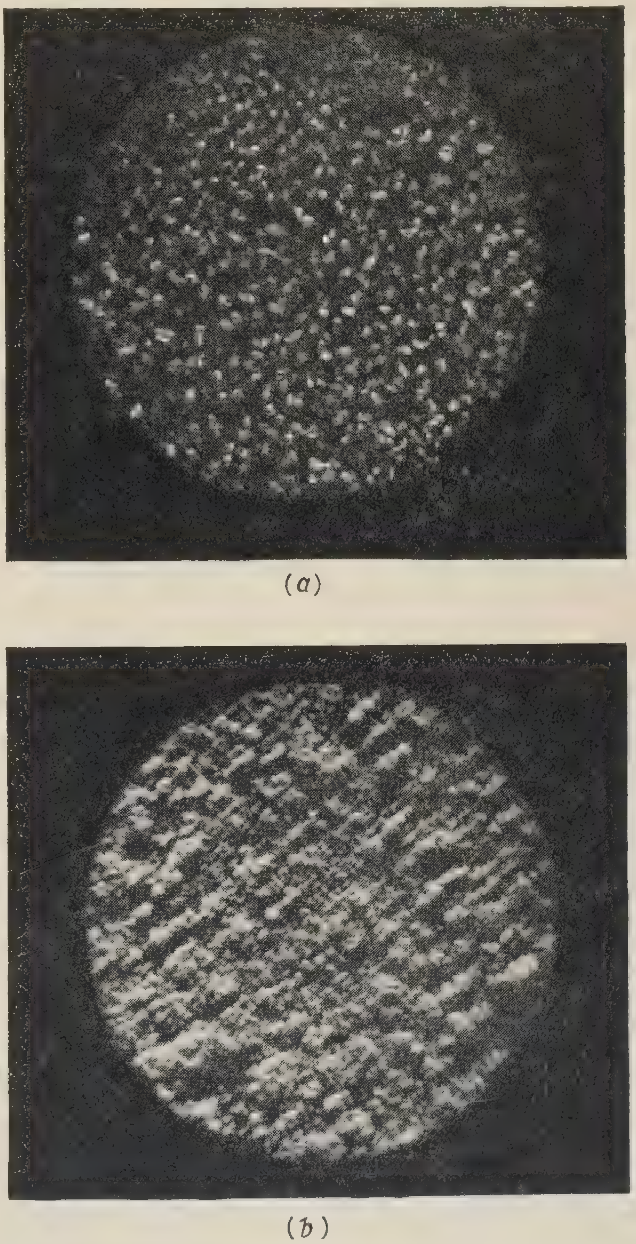


Fig. 5.—The discharge products in an electrode-adjacent cavity in a grade 20 polythene sample tested at a voltage of about twice the initial inception value (×44).

(*a*) Polythene face.
(*b*) Copper face.

Cavity depth, m, 0·045 cm.
Cavity diameter, d, 0·64 cm.
Duration of test, 100 hours.

With the two smallest cavities (0·16 and 0·32 cm diameter), both of which showed extinction, damage to the polythene is confined to the edges. The polythene face of the next largest cavity (0·48 cm diameter) is also damaged mainly at the edge, though a patch of erosion is also visible near the centre. Finally, with the largest cavity (0·64 cm diameter) the damage extends over the entire polythene face except for a narrow ring just inside the periphery. With all the samples the damage to the copper faces consists of a light blue deposit which becomes progressively heavier with increasing cavity diameter.

Portions of the faces of the largest cavity are shown, with higher magnification, in Fig. 5. Damage to the polythene face consists of shallow depressions, together with a distribution of small translucent and apparently crystalline mounds projecting from the cavity face, while the blue deposits on the copper face consist of agglomerations of nodules showing a tendency to alignment on the rolling direction of the foil. These blue deposits were identified as copper nitrate.

(6.2) Polythene Samples with Internal Cavities

With these cavities, the discharge damage took the form of patches of tiny erosion pits, together with small mounds of translucent material which frequently occurred in pairs projecting towards each other from the opposite plane faces of the cavity. There was no obvious correlation between discharge damage and cavity diameter, but the damage appeared to be greater in the cavities of greatest depth, as might be expected in view of the greater energy dissipated per discharge in these cavities.

The damage in internal cavities in polythene was very slight indeed compared with that in electrode-adjacent cavities of the same size and tested under similar conditions (see also Reference 2).

(7) COMPARATIVE 50 C/S AND 1000 C/S DISCHARGE-INCEPTION VOLTAGE MEASUREMENTS

Possible explanations of self-extinction may be divided into two classes:

(*a*) Those involving a partial short-circuiting of the cavity caused, for instance, by the deposition of semiconducting decomposition products on the cavity walls, or by temporary conductivity induced in the dielectric by electron bombardment.

(*b*) Those involving an increase in the electric strength of the gas in the cavity caused, perhaps, by a change in the composition of the gas or by an increase in pressure.

Comparative inception-voltage measurements at two different frequencies provide a method of discriminating between these mechanisms. Suppose that a sample is subjected to a voltage of frequency f_1, and as a result of changes in the conductivity of the cavity walls only, the inception voltage at this frequency is increased by a factor α. If the inception voltage at a second frequency f_2, as determined before and after the test, increases by a factor β, then it is shown in the Appendix that

$$(\alpha^2 - 1)/(\beta^2 - 1) = (f_2/f_1)^2$$

If $f_1 = 50$ c/s, $f_2 = 1\,000$ c/s and α is, say, 3, then $\beta = 1{\cdot}01$. Hence, if mechanisms of class (*a*) only are operative, and the 50 c/s inception voltage increases by a factor of three, the corresponding increase of the 1 000 c/s inception voltage will be only 1 %, and probably not measurable. If, therefore, an increase of the 1 000 c/s inception voltage is observed, mechanisms of class (*b*) must be operative.

Table 8

Relative Changes in the 50 c/s and 1 000 c/s Inception Voltages of Polythene Samples Produced by Stressing at 50 c/s

Sample No.	Type of polythene	Type of cavity	Cavity dimensions: Depth m	Cavity dimensions: Diameter d	50 c/s testing voltage V_T	Discharge-inception voltages: 50 c/s Initial	50 c/s Final	1 000 c/s Initial	1 000 c/s Final
			cm	cm	kV	kV	kV	kV	kV
222	G20	Internal	0·025	0·32	6·0	2·8	5·9	2·9	3·1
240			0·035	0·32	5·0	2·9	5·1	2·9	2·8
244			0·040	0·48	6·4	2·5	4·7	2·8	2·6
259			0·040	0·64	6·6	2·6	5·7	3·0	3·0
260			0·040	0·64	6·6	2·8	6·5	2·9	3·5
191	G7		0·025	0·16	5·0	2·4	4·6	2·2	2·4
192			0·025	0·16	5·0	2·6	4·7	2·4	2·5
193			0·025	0·16	5·0	2·6	5·1	2·4	2·5
196			0·025	0·16	4·5	2·0	4·6	2·2	2·4
197			0·025	0·16	4·5	2·0	4·4	2·2	2·3
198			0·025	0·16	4·5	2·2	5·4	2·3	2·3
199			0·025	0·16	4·5	2·5	5·6	2·5	2·4
213			0·025	0·16	5·0	2·3	4·6	2·5	2·6
214			0·025	0·16	5·0	2·1	4·4	2·4	2·3
262	G20	Adjacent to copper	0·048	0·16	5·2	2·8	3·2	3·1	2·9
263			0·048	0·16	5·2	2·8	5·2	2·9	2·9
205	G7		0·025	0·16	5·0	2·6	4·4	2·3	2·8
206			0·025	0·16	5·0	2·6	5·0	2·7	2·9
230			0·025	0·32	5·2	2·5	5·8	2·5	2·5
236			0·025	0·16	5·0	2·2	7·2	2·3	3·6
238			0·025	0·16	5·0	2·5	3·9	2·3	2·3
261	G20	Adjacent to platinum	0·040	0·64	4·8	1·7	3·2	2·4	2·3
264			0·044	0·16	4·9	2·4	3·7	2·7	2·8

Measurements of this kind were made in nearly all the tests on grade 7 polythene described in Sections 3.3.1 and 3.4.1, and also in a number of tests on grade 20 polythene. With all those samples which showed self-extinction, the increase of the 1 000 c/s inception voltage was negligible or very small compared with that of the 50 c/s value, as shown by the results given in Table 8. Hence, with these samples, it is inferred that self-extinction at 50 c/s is caused by the partial short-circuit of the cavity rather than by an increase in the electric strength of the gas.

(8) SUMMARY OF RESULTS

(*a*) When samples of grade 2 or grade 20 polythene containing internal cavities are tested at voltages greater than the initial discharge-inception value, the discharge-extinction voltage, V_e, tends to increase to the test voltage, V_T, during the first few hours. Within the ranges considered, this effect is independent of cavity diameter, d, cavity depth, m, and test voltage, V_T. When d/m is small, V_e may reach or exceed V_T, so that discharges are extinguished, whereas when d/m is large, V_e tends to remain just below V_T, so that discharges are less likely to be extinguished. The behaviour of samples of grade 7 polythene containing internal cavities is different in that, when d/m is large, V_e does not increase to V_T but remains substantially constant at the initial value.

(*b*) When samples of grade 2 or grade 20 polythene containing cavities adjacent to a copper electrode are tested at voltages greater than the initial discharge-inception value, the V_e/time relationship depends very much on the shape of the cavity. When d/m is small, i.e. less than about 8, V_e tends to increase to V_T and discharges may be extinguished. When d/m is large, i.e. greater than about 12, no such increase occurs and V_e remains substantially constant at the initial value. With intermediate values of d/m, V_e may fluctuate but rarely reaches V_T. Similar, though less consistent, results are obtained with grade 7 polythene. Samples of grade 20 polythene containing cavities adjacent to a platinum electrode show a similar pattern of behaviour, V_e increasing to V_T only when d/m is small.

(*c*) All observed increases of V_e, and the possible subsequent extinctions, are temporary effects which disappear when the sample is rested. If, after a period of rest, a sample is tested a second time, the same type of V_e/time relationship is usually obtained. With samples that show type C behaviour, the initial increase of V_e is frequently faster in the second test than the first.

(*d*) When self-extinction has occurred, short bursts of discharges are sometimes observed at intervals of a few seconds or minutes. Self-extinction is therefore probably a condition of extreme intermittency, rather than of total extinction.

(*e*) When polythene samples containing either internal or electrode-adjacent cavities are tested at 50 c/s, and the discharge inception and extinction voltages increase, so that discharges are possibly extinguished, the increase of the inception voltage at 1 000 c/s is small compared with that at 50 c/s.

(*f*) The nature of the discharge damage in polythene samples containing cavities adjacent to a copper electrode is dependent on cavity diameter. With cavities of small diameter, in which discharges become extinguished, damage is confined to the cavity periphery, whereas with cavities of large diameter, in which discharges do not become extinguished, damage is observed in the central regions also.

Damage in internal cavities in polythene is very slight compared with that in electrode-adjacent cavities of the same dimensions and tested under similar conditions.

(*g*) Self-extinction is not confined to cavities in polythene, but is observed with cavities in other dielectrics also, e.g. rubber and polyvinyl chloride. With these materials, as with polythene, the effects are temporary, reproducible and dependent on cavity shape.

(9) DISCUSSION

The V_e/time relationships obtained with electrode-adjacent cavities in polythene may be interpreted as follows. V_e only rises to V_T with cavities of small diameter/depth ratio, and comparative 50 c/s and 1 000 c/s inception-voltage measurements have shown this increase to be attributable to the partial short-circuiting of the cavity. Also, observations of the discharge damage have shown that, with all diameters, discharges tend to concentrate at the edges, but in the larger-diameter cavities, which do not show self-extinction, they occur in the central regions also. It is therefore probable that the discharges at the edges cause semiconducting tracks to be formed across the curved surface of the cavity, which cause these discharges to be suppressed. In cavities with a diameter/depth ratio greater than a certain critical value, however, discharges at the edges are insufficient to reduce the stress in the central regions of the cavity to less than the inception value, so that discharge sites are established in these regions also. The formation of conducting tracks across the curved surface of the cavity would then suppress the discharges at the edges, but not those in the central regions, so that self-extinction would not occur.

Since the extinction voltage of an 'extinguished' sample tends to return to its initial value when the sample is rested, the conducting tracks must be of a temporary nature. The mechanism of formation is uncertain, but they could be caused either by temporary conductivity induced in the polythene itself as a result of electronic bombardment,[5] or by unstable semiconducting decomposition products. One possibility is that water is produced by oxidation of the polythene, the necessary oxygen being dissolved in the structure (the author is indebted to one of the referees of the paper for suggesting this possibility). The formation of copper nitrate in cavities adjacent to a copper electrode indicates that oxides of nitrogen are produced by the discharges, and so the increase in conductivity could be caused either by water alone, or, more likely, by nitric acid formed by combination of these oxides with the water. Subsequent loss of acid during rest periods by dissociation, diffusion and combination with the electrode material would then account for the gradual recovery of the extinction voltage to its initial value.

Comparative 50 c/s and 1 000 c/s inception-voltage measurements indicate that, as with electrode-adjacent cavities, self-extinction in internal cavities in polythene is caused by a partial short-circuiting of the cavity. However, with internal cavities in samples of grade 2 or grade 20 polythene the V_e/time relationship is very much less dependent on the diameter/depth ratio of the cavity, and type C curves have been obtained with ratios as large as 25 : 1, whereas with electrode-adjacent cavities of considerably smaller diameter/depth ratio, no increase of V_e is observed. Internal cavities, as opposed to those adjacent to a copper electrode, contain no material to react with oxides of nitrogen produced by the discharges, and so the difference in behaviour might at first appear to be accounted for by higher surface conductivities resulting from higher concentrations of nitric acid. This explanation is not entirely satisfactory, however, since cavities adjacent to a platinum electrode show the same pattern of behaviour as those adjacent to a copper electrode; also, the marked difference in behaviour of internal cavities in polythene of grade 7 as opposed to grades 2 and 20 is difficult to account for on a purely chemical basis. These results suggest that some additional conduction mechanism is possible in internal cavities.

When discharges occur in an internal cavity in polythene, the opposite faces of the cavity are bombarded alternately by electrons and positive ions. Thomas[6] has shown that, when a discharge of a given polarity impinges on a dielectric surface, the charges deposited are not neutralized by a subsequent discharge

of the opposite polarity, since incident electrons penetrate the surface and are trapped in positions where they cannot easily be reached by positive ions. If, in an internal cavity in polythene, electrons penetrate the opposite plane faces and are trapped in this way, positive ions will be left in the cavity and will accumulate on the cavity walls. Electrons released from traps by thermal activation[5] could probably rapidly recombine with positive ions, and would then cease to contribute to surface conductivity. On the other hand, free positive ions could not penetrate the polythene surface in order to recombine with trapped electrons, and could continue to contribute to surface conductivity until neutralized by thermally released electrons. The positive ions would probably become attached to other atoms, but provided that the resulting ionic groups were able to migrate over the polythene surface in response to an applied field, they could give rise to surface conductivity. The gradual recombination of the electrons and positive ions would then account for the recovery of the extinction voltage to its initial value when a sample was rested. Such a mechanism could not contribute to conductivity in an electrode-adjacent cavity, since the ionic groups would be discharged on coming into contact with the electrode. The density of trapping sites in polythene is probably dependent on the condition of the surface, and the difference in behaviour of internal cavities in grade 2 or grade 20 polythene, and similar cavities in grade 7 polythene, is probably attributable to differences in the surface states of the three types of polythene, rather than to the different molecular sizes.

The difference in the types of V_e/time relationship obtained accounts for the different rates of discharge damage in internal and electrode-adjacent cavities. In polythene insulation, internal cavities would probably be spheroidal in shape and of small diameter/depth ratio, so that discharges would very likely extinguish or become intermittent. Cavities at the conductor surfaces caused by failure of the conductor-to-dielectric adhesion would be laminar in shape, however, and of large diameter/depth ratio, so that discharges would not extinguish. This latter type of cavity is therefore likely to be the more dangerous.

The possibility of self-extinction must be considered when life tests on dielectrics containing cavities are accelerated by the use of high-frequency test voltages, since there will clearly be no acceleration of the tests during periods when discharges are extinguished, and a gross over-estimate of the dielectric life at 50 c/s could be made.

(10) ACKNOWLEDGMENTS

Acknowledgments are due to Dr. L. G. Brazier, Director of Research and Education, British Insulated Callender's Cables Ltd., for permission to publish the paper.

(11) REFERENCES

(1) Hall, H. C., and Russek, R. M.: 'Discharge Inception and Extinction in Dielectric Voids', *Proceedings I.E.E.*, Paper No. 1618, February, 1954 (**101**, Part II, p. 47).
(2) Mason, J. H.: 'Breakdown of Insulation by Discharges', *ibid.*, Paper No. 1471, March, 1953 (**100**, Part IIA, p. 149).
(3) Davis, R., Austen, A. E. W., and Jackson, Willis: 'The Voltage Characteristics of Polythene Cables', *Journal I.E.E.*, 1947, **94**, Part III, p. 154.
(4) Rogers, E. C., Page, E. B., and Harriss, V. G.: 'A Servo-mechanism for the Study of Self-Extinction of Gaseous Discharges in Cavities in Dielectrics', *Journal of Scientific Instruments*, 1956, **33**, p. 7.
(5) Fowler, J. F.: 'X-ray Induced Conductivity in Insulating Materials', *Proceedings of the Royal Society*, 1956, **236** (A), p. 464.
(6) Thomas, A. M.: ' "Heat Developed" and "Powder" Lichtenberg Figures, and the Ionization of Dielectric Surfaces produced by Electrical Discharges', *British Journal of Applied Physics*, 1951, **2**, p. 98.

(12) APPENDIX

Derivation of the Relative Increases of Discharge-Inception Voltage at two Frequencies caused by Surface Conductivity

A sample of dielectric containing a cavity may be represented by the equivalent circuit shown in Fig. 6, where C_2 represents the

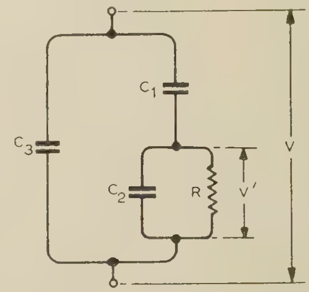


Fig. 6.—The equivalent circuit of a dielectric sample containing a cavity.

capacitance of the cavity; R the effective shunt resistance across the cavity caused by surface conductivity; and C_1 and C_3, the capacitances of the dielectric in series and in parallel with the cavity. The volume conductivity of the dielectric is assumed to be negligible. Let V' be the peak voltage developed across the cavity when a voltage of angular frequency ω and peak value V is applied to the sample.

Then $$V'/V = \omega RC_1[1 + \omega^2R^2(C_1 + C_2)^2]^{-1/2} \quad . \quad . \quad . \quad (1)$$

Suppose that the surface conductivity of the cavity is initially negligible, so that R is very large. If V_i' is the peak voltage required across the cavity to initiate discharges, and V_i is the peak inception voltage measured across the sample, then, at all frequencies,

$$V_i'/V_i = C_1/(C_1 + C_2) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Now suppose that an extinction-voltage/time test is made on the sample at a frequency ω_1, and as a result the inception voltage at this frequency, $V_i(\omega_1)$, is increased by a factor α. Measurements of the inception voltage at a second frequency, ω_2, are made, and $V_i(\omega_2)$ is found to have increased by a factor β. Assuming these increases to be attributable entirely to a decrease in the value of R, the relationship between α and β may now be found.

From eqn. (1),

$$V_i(\omega_1) = \alpha V_i = V_i'(1/\omega_1RC_1)[1 + \omega_1^2R^2(C_1 + C_2)^2]^{1/2} \quad . \quad (3)$$

$$V_i(\omega_2) = \beta V_i = V_i'(1/\omega_2RC_1)[1 + \omega_2^2R^2(C_1 + C_2)^2]^{1/2} \quad . \quad (4)$$

Eliminating R from eqns. (3) and (4),

$$C_1^2(V_i/V_i')^2(\omega_1^2\alpha^2 - \omega_2^2\beta^2) = (C_1 + C_2)^2(\omega_1^2 - \omega_2^2) \quad . \quad (5)$$

Substituting for (V_i/V_i') from eqn. (2),

$$\omega_1^2\alpha^2 - \omega_2^2\beta^2 = \omega_1^2 - \omega_2^2 \quad . \quad . \quad . \quad . \quad (6)$$

Therefore $$(\alpha^2 - 1)/(\beta^2 - 1) = (\omega_2/\omega_1)^2 = (f_2/f_1)^2 \quad . \quad . \quad (7)$$

where f_1, f_2 are the frequencies of the two test voltages.

DISCUSSION ON

'MECHANICAL STRENGTH OF POWER TRANSFORMERS IN SERVICE'*

Before the East Midland Centre *at* Nottingham *22nd October, the* Rugby Sub-Centre *at* Rugby *10th December*, 1957, *the* North Staffordshire Sub-Centre *at* Stafford *13th January, the* Western Supply Group *at* Bristol *17th February, the* South-Western Sub-Centre *at* Plymouth *18th February, and the* South-East Scotland Sub-Centre *at* Edinburgh *15th April*, 1958.

Mr. D. H. Smith (*at Nottingham*): Taking the paper as a whole, one must confess to a feeling of depression. It makes one wonder why transformers ever withstood short-circuits at all. Strengths are worked out and the ultimate strength is something less than any of these. The statements in Section 9.3 (iii) conflict with Section 9.3 (iv).

Figs. 6 and 7 show the stress/strain relations for transformer insulation, and it is indicated that, when transformer insulation is stressed, it does not return to its original condition and the operation is a progressive one. I wonder if this is really true in practice—whether windings as made are more elastic than is indicated. When some time elapses between short-circuits it may be that the winding is more elastic and does return nearer to its original dimensions than is indicated.

In the construction of transformer windings we have a mixture of metal, paper, hardboard, pressboard and various other materials. Basically the windings are subjected to various forces as explained in the paper, and to resist these, two things are necessary. First we must build windings that are absolutely solid and non-compressible, and secondly we must balance the windings perfectly so as to reduce axial forces to a practical minimum. I suggest that much more can be done than is being done to produce really solid transformer windings.

Some time ago tests were made on transformer insulation to determine the amount of compression obtained by the application of steady forces, and a compression curve was obtained. If a transformer coil is dried out in the oven under continuously applied pressure, shrinkage will occur which will eventually become a maximum and the coil will be fully shrunk.

This particular technique has recently been applied to a 2·5 MVA transformer which failed during short-circuit. The impedance was less than 5% and the damage caused was very extensive. After many attempts to produce a sound job the transformer was treated as above, the coil being fully shrunk under heat and dry air. The result was satisfactory in that the transformer was tested at a short-circuit testing station and appeared to be perfectly sound.

Assuming that we can obtain a fully compressed winding, it is extremely difficult to ensure that axial forces are a minimum. Obviously in a transformer the windings are designed to obtain as perfect a magnetic balance as possible, and it would be most desirable to be able to test this feature on a transformer after assembly and prior to tanking.

In the test the transformer would be subjected to approximately full-load current through the windings, and the reactive flux components measured. If this could be made to work it might give a valuable indication of the balance of the windings before final assembly, when it might be possible to adjust before tanking. Is there any possibility of such a method being developed?

I am puzzled by a statement in Section 7.2 that a 3-phase 3-leg transformer is much more favourable than a 5-leg transformer with the mechanical stresses in the outer phases nearly doubled and the short-circuit strength reduced. It appears that this is governed by the factor l in eqn. (5) and I would have thought l related to the winding length, in which case I do not see any difference between the arrangements shown in Figs. 4(*c*) and 4(*d*).

Prof. J. E. Parton (*at Nottingham*): The paper deals almost entirely with concentric windings, and very little is given about interleaved windings. I should like the author to explain how interleaved windings are dealt with and how his theories have to be modified. On the surface, it would appear that the coaxial forces which are most prevalent in ruptured transformer windings would be eliminated with interleaved windings.

One rather drastic measure to contain the rupturing force in transformer windings would be to enclose them in concrete or some other synthetic bonding material. This, of course, is done with very small transformers. Could the author give his views on whether such enclosed windings are ever likely to be made for large power transformers?

Mr. R. J. Pendlebury (*at Nottingham*): If each successive short-circuit distorts the windings a little, are they eventually so distorted as to be visible before the transformer breaks down? Is it, in fact, worth inspecting them?

Mr. R. C. Gething (*at Nottingham*): I should like to know whether clamping-down bolts have been tried with a left-hand and right-hand thread—a nut with a left-hand thread on the bottom and one with a right-hand thread at the top. It could then be screwed up from the bottom as well as down from the top. The centre of gravity of the coils would then presumably remain the same.

Mr. J. D. Pierce (*at Nottingham*): Presumably when fault throwers operate they do shorten the life of the transformer to some extent.

In Table 3 the number of short-circuits is shown, but it always seems rather difficult to see the effect on any transformer of a short-circuit. I should like to know how have these things been recorded, because short-circuits do take place, but having regard to the plant behind the transformer, the number of transformers, etc., it seems rather difficult to say which particular transformer has had a severe shock. If it has had a cable fault, with the Grid system connected, the effect must be considerable. It might be worth while incorporating in the transformer instrumentation a relay or some recording device that can indicate the shock to which the transformer has been subjected. From the point of view of the engineer operating the transformer it is most important to know the history with regard to short-circuits.

Mr. H. W. Oldham (*at Nottingham*): The author states that transformers with reactances above at least 12% will be inherently protected against the effects of external short-circuits, and he mentions a figure of 18·6% with respect to one particular unit. I should be glad if the author could give more details of this percentage reactance figure as related to transformer size, since a large increase in reactance would introduce certain problems in operation.

With regard to short-circuits which may affect the life of a transformer, the author suggests that only short-circuits in, or just outside, the substation should be counted. As transformers

* Norris, E. T.: Paper No. 2317 S, February, 1957 (see **104** A, p. 289).

may be moved from one substation to another during their life, or system conditions may change giving rise to wide variation in fault level, would it not be better to count only those short-circuits where the calculated fault current exceeds a certain percentage, say 75 or 80%, of the theoretical maximum value which could be obtained from that transformer assuming infinite input? I should like to have the author's comments on this percentage-basis suggestion, as it would provide a fixed yardstick for each individual unit irrespective of its situation, the position of the fault or system conditions at the time.

I am not so directly concerned with transformers of 30 MVA as with units of 24 MVA and below, and I should like to have the author's comments on the effect of short-circuits on the life of the smaller units and the mechanical stresses which then arise.

Mr. P. H. G. Allen (*at Rugby*): I was pleased to note that, in his reply to the London discussion, the author refuted a suggestion that he had confined his treatment to disc windings because of any superiority of this type of winding over the layer type for high-voltage use. The magnetic design of the layer-type winding is, however, complicated by some of those factors which contribute to its excellent electrical performance. Boyajian has remarked* that 'the freedom of the transformer designer to use the most economical or convenient winding arrangement in meeting a particular requirement is handicapped by his inability to calculate reliably (and with a reasonable amount of labour) the reactances and forces of those winding arrangements which depart considerably from certain simple symmetrical types and proportions'. We have therefore been studying the use of the electrolytic-tank analogue to map the leakage magnetic field. A brief description of our technique has been published,† and we hope that fuller details will be available in due course. Fig. B shows the type of flux plot that can be obtained making the usual assumptions. It is a straightforward case used purely as an example. Flux quantities are referred to the total leakage flux, which here passes between the inner and outer turns at the centre plane. Measurement of the potentials assumed by each electrode gives most information. For example, in the case of force calculations, we plot these potentials against distance along any layer, as shown for the outer layer in Fig. C. From the slope of this curve at any point can be derived the radial component of flux density which is needed for force and eddy-current-loss calculations.

Mr. H. E. Pettit (*at Stafford*): In contrast to the attention given to other suggested modes of failure, the compression force mentioned in Section 6.1 has been dismissed in a cursory manner. Although it is possible to meet this stress even on the largest transformers, adequate support taken back to the core at frequent intervals is necessary, otherwise the force in the window can be high enough to be the first cause of failure. However, assuming this to be effectively dealt with, I agree with the statement in Section 7.2 that the displacement force is the most likely prime source of failure.

The actual onset of failure is well illustrated in Fig. 8. The turning over of the conductors allows enough movement, however minute, to increase the value of d; the force increases correspondingly and progression to failure ensues. Although the subject disc-coil winding in Fig. 7 appears to withstand quite a high stress under the particular application (i.e. by hydraulic press), the order of compression shown indicates that, under short-circuit conditions, the increase of displacement would start failure at an early point on the curve. Furthermore, in its application to power transformers this curve is probably misleading because it refers to a $0 \cdot 28\,\text{in}^2$ conductor, which would surely not be used on a transformer of any size. A wire such as $0 \cdot 5\,\text{in} \times 0 \cdot 1\,\text{in}$ for instance, would have a much greater tendency to turn over.

I am surprised at the intensity of stress referred to throughout the paper. We consider a safe stress to be about $\frac{1}{2}$ ton/in^2. It would be interesting to see the permanent strain characteristics of a coil stack at this stress.

The type of construction exemplified in Fig. 16 has often been referred to, although I have never met its commercial application. To realize the transfer of stress entirely along the insulation, and prevent its accumulation from copper to copper, requires the intervening spacers to form a very stiff bridge from inside to outside. The necessity for sufficient area of insulation to take the stress will also require a large radial gap between the winding and the tubes, both inside and outside it. Thus, if correctly carried out, this construction will have a very poor space factor.

Mr. S. Palmer (*at Stafford*): Does the author agree that an important type of mechanical stress, not discussed in the paper, is the bending stress on the outer turns of the windings?

In general, large high-voltage transformers of the kind discussed in the paper are tending, in proportion to previous units, to have short window heights, because of transport limitations; large differences between high-voltage and low-voltage coil widths, because of the extra insulation in the high-voltage winding; and large yoke clearances because of the required insulation to earth. All these factors increase the radial component of leakage flux density at the ends of the winding, and result in increased forces on the end turns which tend to bend where they are not supported by spacers. Since the high-voltage conductor itself tends to be of smaller section, the bending stresses increase even more than the forces.

This leads me to ask whether the author considers that the tests described in Section 9.2 simulate actual conditions sufficiently well. In these tests, the turns themselves are not subject to individual forces; the rubbing action produced by differential movements between conductors subject to different rapidly alternating forces is absent; and the electrical stresses between turns are presumably quite different from those in actual units.

Has the author any experience of the Waters method (Reference 12 of the paper) of measuring the radial component of leakage flux as a routine check of the electromagnetic dissymmetry in new transformers?

Mr. A. E. T. Luker (*at Stafford*): I should like to refer to the statement in the paper that a power-transformer winding is composed of copper, paper, pressboard and twine. Since the transformer is immersed in a tank of oil, the materials other than the copper would tend to absorb oil, thus altering their compressibility factors. Would the factors of mechanical strength given for the dry state be subject to change in the oil state?

Mr. J. Wainwright (*at Stafford*): The correlation between service experience and the author's calculations is so close that one is tempted to check whether any seemingly important factors have been neglected. There are two or three such factors which are not mentioned in the paper and which could possibly have appreciable effects on the mechanical characteristics of the insulation.

First there is the effect of temperature on the moduli quoted in Table 1. Whereas these figures were presumably taken at room temperature, they are applied to calculations on apparatus where the operating temperature may be in the region of 100° C, or even 250° C.

Secondly, although the test results were presumably obtained by static loading, in practice the load is applied fairly rapidly,

* Boyajian, A.: 'Leakage Reactance of Irregular Distributions of Transformer Windings by the Method of Double Fourier Series', *Transactions of the American I.E.E.*, 1954, Part III, p. 1078.

† Allen, P. H. G., and Foster, J. H.: 'Transformer Magnetic Field Plotting by Electrolytic Tank', *Review of Scientific Instruments*, 1957, **28**, p. 1095.

i.e. in a few milliseconds. The characteristics of many materials are dependent on the rate of application of load.

Thirdly, a factor of supreme importance is the effect of ageing —mainly due to thermal agencies. Most insulating materials are subject to adverse changes in mechanical characteristics as a function of time and temperature. This is, in fact, the chief test method by which the life of transformer insulation is judged.

It would appear that additional correction factors are needed to take these effects into account.

Finally, it is assumed in the paper that a short-circuit results in one application of force, whereas each short-circuit is actually a series of pulses. Normally this would be unimportant, since the forces decrease rapidly, but in a transformer the effect could be rather different. For instance, if the time-constant of a massive copper winding damped with oil-soaked paper or pressboard is longer than the time between pulses, subsequent pulses may be applied at a time when the winding displacement is a good deal greater than it was originally.

Mr. D. H. Ryder (*at Stafford*): In the case of copper, Fig. 1 shows the manner in which yielding takes place, but cellulose materials behave quite differently. They have no crystalline structure, and although Fig. 6 shows permanent displacement after stressing, there is probably a recovery with time, which will make the displacement due to short-circuit less marked. Such an effect would tend to mask the repeated yielding processes which are postulated in the paper.

Section 9.1 gives further consideration to the axial displacement of windings due to short-circuit pulses, and indicates, as may be expected, that the end insulation of a winding is responsible for the major yielding effects. Thus, for higher-voltage windings, the problem of compressible end insulation becomes more and more severe. Conditions can be improved considerably if the high-voltage line lead is brought into the centre of the winding, because, for this arrangement, and when the winding has an earthed neutral, the end insulation is merely nominal. It should be realized that the major gain for such an arrangement is not in the high-voltage winding itself but in the low-voltage and tapping windings, which have similar end clearances. These windings are generally nearest the core and consequently have higher axial forces. The reduction in compressibility of the reduced end insulation of these windings is a most desirable feature in core-type transformers.

Mr. G. J. Caplen (*at Stafford*): I am particularly interested in the cumulative effect of short-circuits, as I design large furnace transformers, which are short-circuited very frequently. In Section 10 the author states that the transformer he is considering will withstand an unlimited number of faults of 7·4 times the normal full-load currents, but I presume that the asymmetry factor has been taken into account, so that this represents a reactance of 24·4% and not 13·5% as would at first appear. I feel that the asymmetry factor should be given greater prominence. B.S. 171: 1936 specifies the short-circuit which a transformer should be capable of withstanding, but does not mention asymmetry, although the mechanical forces in a fully asymmetric short-circuit are 3·24 times those of a symmetrical short-circuit. Viewed from another angle, when a short-circuit test is done, it is often difficult to persuade the customer that the test need only last for, say, 20 cycles, since all the damage is done on the asymmetric peaks, and prolonging the test for several seconds only makes it more difficult to find the original cause of the failure.

The author describes some practical tests on coil stacks. Whilst agreeing that the turning over of the conductor is the most usual failure, I feel that these tests have very little use, because of the difficulty in translating the results from a test where the force is applied very slowly and exactly axially to the practical case where the force is applied suddenly and at an angle to the coil stack.

Mr. M. J. Little (*at Bristol*): A natural reaction is to consider possible solutions to the problem of preventing transformer breakdown under extreme fault conditions. To increase the transformer reactance above the acceptable 10–12%, with its associated regulation difficulties, does not provide a satisfactory solution.

Transformer strength largely depends upon the characteristics of the insulation used, and in this respect, Section 9 of the paper must be considered the most important. Cumulative shrinkage of insulation affords the main source of danger by increasing the extent of electromagnetic unbalance and so producing excessive axial forces. This is unavoidable, since large power transformers may have one-third to one-half of their axial length occupied by various insulating materials, so that an overall shrinkage of only 1% will produce considerable unbalance. These materials are subjected to a continual thermal cycling, mechanical vibration and switching forces, and yet it seems that too little research has gone into their development. What is required is a product of high tensile and crushing strengths, easily impregnated and impervious to heat cycling. Possibly a development along the silicone line may provide the answer.

Two other solutions also present themselves. In most cases the position of maximum axial force due to electromagnetic unbalance occurs in the winding turns nearest the yokes, which suggests further reinforcement and grading of windings and insulation on those regions, subject, of course, to impulse considerations. Section 9 indicates that an increase in insulation bearing area a reduced p, with a subsequent increase in K_c, K_0 and K_1. The limitation is due to the consequent reduction in cooling area. However, present trends in turbo-alternator design provide liquid and gas cooling ducts within specially shaped stator conductors, and it should be possible to provide some form of 'internal' system, in extreme cases, for transformer cooling.

Finally, the prediction of transformer life seems ideally applicable to another situation more potent than the case of the power transformer. The occurrence of arc-backs in rectifiers is basically random in nature, and since it is apparently not practical absolutely to eliminate the possibility of arc-backs the rectifier-transformer designer must make allowances for the cumulative effects of repeated short-circuits, which may occur at the rate of several per year. Can the author inform me whether, in fact, he has applied his theory to the relatively abundant cases of short-circuits on rectifier transformers?

Mr. M. S. Hawker (*at Bristol*): Is the damage described in the paper likely to occur in transformers of 20 MVA and below?

Mr. A. H. McQueen (*at Plymouth*): During short-circuit and at other times on overload, it seems possible that charring of the paper insulation could occur, thus leaving space for movement of the windings, and a new set of mechanical conditions would be set up.

With regard to the use of Buchholtz protection to give adequate protection on these large transformers, would it not be desirable to have a high-speed protection and thus limit the damage to the transformer?

Mr. W. C. Thomson (*at Edinburgh*): While it is true that, when erected and commissioned, the system apparent power must follow the apparent power rating of the associated switchgear, the wrong impression may be created in that at the system design stage for the voltages and size of the transformer under discussion the converse is usually the case. The design of the system is dictated primarily by considerations of load, possible sites and capacity for generating plant and reliability of firm capacity at the load centres. These considerations obviously

produce a number of alternatives which result in a final selection, and at this point the system apparent power is known. This calls for switchgear of a known rating, which, at that stage, may not exist, and manufacturers are consulted as to the possibility of uprating existing designs or introducing new ones. Fortunately for the supply undertakings, this development of switchgear is a continuous one and usually results in the requirements of system design being met in full by the time it is required. Needless to say, such development is closely studied and encouraged by the supply undertakings and others concerned with supply systems. It is maintained, therefore, that the rating of switchgear follows the requirements of the system, and, of course, a transformer designer has to take cognizance of these facts, as the author so rightly points out.

With regard to what the author refers to as 'dead short-circuits', or in other words 'system faults', these, for the most part, begin as faults from line to earth and may develop within a short space of time to line-to-line or 3-phase faults, usually with a line-to-earth fault at the same time, and it is by no means an easy task after every occurrence to decide exactly what has taken place. Surely the type of fault and its severity and sequence affect the matter when related to possible shortening of life and damage to a transformer. Another factor to be considered is the effect on insulation and the manner in which the fault is cleared from the system, since damage may be caused by over-voltages. If we add to this the shortening of transformer life by lightning surges just not high enough to be dealt with by protective devices installed for the purpose, we see that the faulted transformer presents a very difficult case for diagnosis.

On the question of performance in service, the author refers to 'a modern well-run system', and it is felt that, at present, all systems—in this country, at any rate—are well run. There is always the possibility of short-circuits and earths being left on the system when switching in. This is no fault of the running of the system but is attributable entirely to the operator. Faults occur owing to atmospheric and weather conditions, accidental damage by such things as earth-moving equipment, deterioration of insulation on equipment, etc., and cannot be laid at the door of the personnel concerned with running the system.

Mr. R. W. Flux (*at Edinburgh*): Until recently there have been widely divergent views on the basis of calculation of mechanical forces. It is not clear whether the satisfactory service operation of certain transformers is due to sound design or lack of short-circuit power when they have been subjected to faults. I suggest that manufacturers should collaborate in working out an agreed basis for calculating forces, which could be published as a recognized standard for the information of the customer.

The available short-circuit testing facilities are so limited in this country, and, according to Reference 1 of the paper, even more limited in the United States, that it appears that the only practicable way to assess the performance of a range of different makes of transformer would be to subject them deliberately to a series of short-circuits whilst they are connected to the supply system. I believe that this method is regularly adopted in France.

Until both manufacturer and user are completely satisfied that their transformers will withstand the worst possible conditions that can arise in service, I think it would be most imprudent to make any reduction in strength on account of specified series impedance. Furthermore, even when we are certain that our force calculations are completely reliable, the designer should always attempt to avoid winding arrangements which, however attractive from another point of view, result in mechanical forces greater than those that would arise with alternative dispositions.

Mr. E. T. Norris (*in reply*): Messrs. Pierce, Oldham, Wainwright and Thomson ask questions concerning the definition of a short-circuit in service when using the formulae given in Section 10 to determine the expectation of life. This definition is not mine but that of the operating engineers providing the service records.

In particular, the cases in Table 3 were clear cut in that the short-circuits were mainly due to barrage-balloon faults. In general, the definition follows statistically from the service records. A summary of world-wide experience gathered since the paper was presented indicates that hitherto an average transformer has a nominal short-circuit once in three years, and consequently (using the factor 9 from Section 10) the equivalent of one fully asymmetrical dead short-circuit in 27 years or, roughly, once in a lifetime. It is very fortunately not necessary, therefore, that a transformer shall be completely short-circuit-proof for any number of faults or indeed have an internal reactance large enough for this purpose.

The dimension l mentioned by Mr. Smith is, as shown in Fig. 4, for the maximum force in the window of the core. Outside the window it is more dependent upon the winding length L.

The concepts in the paper can be applied equally well to shell-type or Mr. Parton's interleaved windings, using the appropriate formulae as indicated in Section 3.

In reply to Messrs. Caplen and Little, short-circuit testing transformers and rectifier transformers which have to withstand frequent short-circuits are specially designed and constructed for this purpose. This is possible because they are usually relieved of many thermal, impulse and other insulation stresses which restrict the mechanical design of large high-voltage power transformers. The resin or concrete cast construction would come within this category. A short-circuit may last for one second or more, but the worst mechanical stresses fall away rapidly due to asymmetry after the first half-cycle, as shown in Fig. 4 of Reference 4.

In reply to Mr. Pendlebury, the progressive distortion of the winding insulation is usually internal, since the inner lower-voltage winding probably has the higher stresses, as shown in cases L and M or Section 11.1.

Mr. Gething's proposal is ingenious, but the ideal of providing such balanced clamping independently on all windings is not practically simple, especially when very high voltages are involved. Windings are so weak mechanically compared with core steel that stresses within the winding strength are unlikely to affect the transformer core, especially as they are also very infrequent.

The recording of short-circuit stresses described in Section 11.2, when necessary, is affected by any change in the short-circuit level, and Mr. Oldham suggests one method of providing a fixed yardstick.

I agree with Messrs. Palmer and Caplen that the static hydraulic-press tests described in Section 9.2 do not completely represent short-circuit stresses dynamically, but they are nevertheless a practical approximation. The alternating forces are rapidly reduced by the decrement factor mentioned above.

The Waters method of measuring indirectly the mechanical stress within certain windings is highly ingenious, and has been accorded world-wide recognition among transformer engineers.

Mechanical-strength calculations should, as Mr. Luker suggests, be based upon the oil-impregnated characteristics of the insulation. In general, the mechanical strength is affected much more by moisture absorption than by oil impregnation. Similarly, the calculations should also be based on the maximum temperature at the instant of short-circuit, say 100° C. The mechanical stresses are greatly reduced by the time the standard final temperature of 250° C is reached.

Messrs. Wainwright and Ryder both refer to the complicated

and variable mechanical characteristics of insulating materials. There is need for more detailed study, as outlined in my reply to the London discussion.

The centre-lead high-voltage winding has the advantages suggested by Mr. Ryder. These may, or may not, be offset by the additional conductor insulation due to the doubling of the turns, i.e. an increase in t_1 of eqn. (14).

Mr. Caplen's figure of 13·5% is the correct one. The basis of calculation in the paper is described in Section 5.

In reply to Mr. Hawker, the vulnerability to damage depends, in general, more upon the frequency and severity of short-circuit conditions than upon the apparent power rating. The position is summarized by the first sentence of Section 11.1 and by Section 13(*e*).

DISCUSSION ON 'ELECTRICAL EQUIPMENT FOR RECTIFIER LOCOMOTIVES'* AND 'CIRCUIT CALCULATIONS FOR RECTIFIER LOCOMOTIVES AND MOTOR-COACHES'†

Before the NORTH MIDLAND UTILIZATION GROUP *at* LEEDS 15*th October*, *the* NORTH STAFFORDSHIRE SUB-CENTRE *at* STAFFORD 28*th October*, *the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE 25*th November*, *the* MERSEY AND NORTH WALES CENTRE *at* LIVERPOOL 9*th December*, 1957, *and the* SOUTH MIDLAND CENTRE *at* BIRMINGHAM 6*th January*, 1958.

Mr. G. W. Graham (*at Leeds*): The general interest in rectifier locomotives may stem, to some extent, from the fact that the equipment of such a locomotive involves an extremely wide range of component parts. Designers of a.c. and d.c. machines, rectifiers, transformers, control gear, etc., find themselves contributing to the development of the locomotive. This very diversity of equipment presents special problems, both administrative and technical.

There are administrative problems because of the need for liaison between departments or even companies with no background of co-operation on close-knit projects, and technical problems because of the need to arrive at the best overall design of locomotive. Many compromises are involved, as between, for instance, transformer and radiator weight and space. The correct compromise need not be the same as that found in static industrial applications. This optimization of design is a problem in itself, deserving careful thought and attention. The difficulty is considerable in the case of the choice of the supply system for auxiliary machines, not mentioned in the paper. I would be interested in the authors' views on that matter.

Some savings in rectifier space and weight may be expected in time from the application of semiconductors, but in an 80-ton locomotive, rectifiers already account for only some 2 tons, complete with auxiliaries and cooling equipment. Greater help would result from even a small percentage saving on the 8 or 9 tons weight of the oil-cooled transformer and choke. Since transformer design is well established, do the authors see any hope of such a reduction, for instance by closed-circuit gas cooling?

Mr. W. G. V. Dunn (*at Leeds*): With reference to Section 4.4.2 of Paper No. 2339, Fig. 17 shows that at the instant 2 there is a considerable increase in the instantaneous peak voltage between commutator segments over the d.c. case, owing to the pulsating current, and thus flux, in the armature and main field. Section 4.4.4 states that a non-inductive main-field diverter can reduce the main-field ripple component very considerably, and thus also reduce the instantaneous peak voltage, which is possibly a valuable contribution if commutation is difficult. This Section also brings out the point that this diversion of the main field is limited because of the danger of flashover under transient conditions. Would the authors amplify their remarks on this matter, since it would seem that the removal from the motor of some of its protection against line surges and supply variations must be very carefully considered with respect to the possible improvements in rating and commutation gained, especially if the resulting increase in ripple current is significant enough to offset the above gains.

Mr. G. W. R. Patterson (*at Leeds*): In Section 4.3.2 of Paper No. 2339 the authors mention that fuses are used to protect semiconductor rectifiers, which have a short heating time-constant, from being damaged under fault conditions.

Is this a good method when one considers what may happen in service? Traction-motor flashovers, although not necessarily common, are not an unknown feature of electric traction, and many of these are of a minor nature not seriously detrimental to the motors. It is quite often possible to re-apply power immediately and there is no 'on line' failure.

With semiconductor rectifiers protected by high-speed fuses, these minor flashovers will blow the fuses every time, and this will probably require skilled maintenance personnel and cause the unit to be failed in service until the fuses are replaced. On the other hand, if the fuses do not act quickly there is every possibility of damaging the rectifiers because of their very-short-time overload capacity.

Mr. S. S. Brice (*at Leeds*): The rectifier could be oil-cooled, perhaps using the same system as that used for the transformers. I would like to have the authors' opinion on the relative merits of resistance and reactance tap-changing.

Mr. J. L. Morgan (*at Leeds*): Comparisons made in Paper No. 2339 between bi-phase and bridge connections for rectifiers indicate that, for a given power, the transformer in the bi-phase system would be approximately 20% bigger than that required in a bridge circuit. Furthermore, in Section 3.3.1.2 it is stated that twice as many contacts are required on the tap-changer in a bi-phase system as compared with the number required for the bridge circuit. These two considerations suggest that the bridge circuit is to be preferred for traction applications.

The loss in rating owing to eddy-current and hysteresis losses given in Table 2 appears to be high. This may be due to the

* CALVERLEY, H. B., JARVIS, E. A. K., and WILLIAMS, E.: Paper No. 2339 U, March, 1957 (see 104 A, p. 341).
† CALVERLEY, T. E., and TAYLOR, D. G.: Paper No. 2340 U, March, 1957 (see 104 A, p. 355).

main flux being allowed to ripple. Could the authors state whether or not this was the case?

In Section 4.4.2 it is stated that, although some standard d.c. traction motors are performing very well on pulsating current, ideally the interpole-flux circuit should be fully laminated and unsaturated. For many traction applications it is necessary to design motors up to the safe limit both for commutation and heating in order to obtain the required output from the available space. Under these conditions, it is essential that a fully laminated and unsaturated interpole-flux circuit should be employed if the motor is to operate satisfactorily on a pulsating d.c. supply. On the other hand, there is no doubt that if standard d.c. motors have an adequate margin for commutation and heating when operating on a smooth d.c. supply, they will operate satisfactorily on a pulsating d.c. supply. The question of when to laminate the interpole-flux circuit must be determined after giving careful consideration to the commutating and heating conditions for each case.

Fig. 18 shows the motor inductance up to only 115% of the rated current. Since it is usual for traction motors to accelerate at 2–2·5 times the rated current, it would be interesting to see the curves extended to these values, since the machine inductance will fall as the motor saturates, thereby causing the ripple current to increase with load.

The weight of the d.c. reactor given in Section 4.4.3 is of little value unless some indication is given of the extent to which the reactor inductance will fall owing to saturation when operated at currents in excess of the rated value.

With reference to the last paragraph of Section 4.4.4, I believe that a non-inductive diverter connected across the main field has been used on some French locomotives in order to reduce the main flux pulsations.

Mr. K. D. Phillips (*at Stafford*): Paper No. 2339 mainly describes arrangements with individually-motored axles; coupled wheels and large common motors possibly give better adhesion and suspension. Would a larger motor permit a higher rectifier voltage with simple circuits? Dual a.c. systems entail some risk of maloperation. What type of apparatus is used for the automatic change-over, and how is the operation checked?

Many rectifiers associated with rolling-mill-drive motors have both grid control and transformer on-load tap-changer. If a fast voltage regulator, e.g. magnetic amplifier, is coupled to the grid gear, the tap-changer steps are smoothed out. The overall combination gives very close control and permits constant-current acceleration. Would this arrangement improve locomotive performance? The grid control could be adapted for regenerative braking, which would appear to be potentially of greater value on an a.c. rather than a d.c. system, because the a.c. system has greater spacing of substations in which power flow is inherently reversible. The use of a tap-changer eliminates the resistive losses of a d.c. locomotive. Have the authors any data on the relative all-day losses of a.c. and d.c. locomotives on a typical duty? Transformers introduce oil-fire risks or gas risks if non-inflammable fillings are used. What are the authors' views on this matter?

Paper No. 2340 refers to additional studies on the effects of capacitance. Has this work altered the conclusions given in the paper? Table 7 shows a harmonic r.m.s. current of about 20% of the fundamental current. Would a substantial reduction in the harmonic current, effected by filters on the locomotive, show any saving in contact wire section or substation spacing? Would the authors also comment on the possibilities of power-factor correction?

Mr. J. A. Richardson (*at Stafford*): In Section 4.1.1 of Paper No. 2339 it is stated that the use of air as the insulating and cooling medium promotes lightness. Although oil weighs more than air, it is so much more efficacious as an insulating and cooling medium that an oil-filled transformer is more often lighter and smaller, and furthermore air must be kept clean. Arc-starvation surges practically never trouble an oil-filled transformer, but need care in an air type. Current densities 'several times greater than' normal are customary. There are risks in excessively forced cooling.

It is argued that the shell type is better than core type, but there are more than two ways of arranging windings on a core that can be developed into a good transformer.

Paper No. 2340 shows that the primary current of a single-phase rectifier can exceed by an important amount the figure given in the I.E.C. standard for mercury-arc convertors in Table 2.

The following simplified outlook on the last part of the paper would appear helpful for explanatory purposes or rough estimation. Fig. 4(*a*) shows the primary current with perfect smoothing. If there were no smoothing and the load were purely resistive, the current would be a sine wave with no harmonics, having an r.m.s. value of 1·11 times its mean value. With smoothing neither perfect nor absent, therefore, harmonics will be reduced and the current will be increased by a percentage of about the amount shown in col. B over that in col. A in Table 4. An increased primary current for a given power output involves lower power factor. Overlap is less than with perfect smoothing because commutation takes place at low current owing to the wave approaching sinusoidal shape.

Mr. J. L. Hewitt (*at Stafford*): Fig. 3 of Paper No. 2339 shows the relative weights of 4-pole and 6-pole traction motors. On the basis that the electrical equipment of a 4-motor locomotive will be limited to a maximum of 80 tons and that the four motors may total 12 tons, it is interesting to note a possible saving in weight of something like 1½ tons by using 6-pole instead of 4-pole motors. It is probable that the extra labour cost involved in the manufacture of the machine having a larger number of poles would not exceed the saving made by the reduction in weight. Could the authors give a graph similar to Fig. 4 showing the relative costs of the two sets of machines?

The authors indicate that the higher current of the 6-pole machines is a disadvantage for the mercury-arc rectifier and for the control equipment. It is presumed that more expensive rectifiers and control equipment are thereby required, and it would therefore be interesting to have a more detailed comparison in view of the relatively large change in motor weights already noted.

Mr. A. E. Bishop (*at Newcastle upon Tyne*): In Section 3.2.2 of Paper No. 2339 reference is made to stepless regulators. I wonder whether lack of progress with this form is due to the fact that the locomotives are made by those who do not manufacture regulators. I suggest that both groups combine and produce a first-class job. Have saturable reactors been considered for stepless voltage control? With stepped control, how many steps and notches are used?

Section 4.1.1 gives no data on the operating temperatures of the transformers. Are they as laid down in B.S. 171? Could the H-type transformer be used, possibly with silicone fluid cooling? Could not the outer surface of the locomotive be used as a radiator to take advantage of natural cooling from movement of the locomotive?

Section 4.1.3 is simply standard textbook material. I want to know the relative merits of the various types of transformer for the purpose in mind. Table 2 should be extended to cover the 50% ripple mentioned in Section 4.4.3. For this level, the rating would appear to drop by 12–15%.

We are given no information about the generation of overvoltages either during normal working or under fault conditions.

This, coupled with absence of fault protection, suggests that faults do not occur in the authors' equipment.

Mr. K. C. Parton (*at Newcastle upon Tyne*): With regard to the desirability of a stepless control in preference to on-load tap-changing transformers, I wonder whether the authors have given any consideration to the basic technical solution of using a large d.c.-controlled saturable reactor feeding all the traction motors in parallel, each motor having its own individual bridge rectifier of the semiconductor type. The advantages would be the need for a minimum amount of auxiliary control gear and the fact that any setting of the d.c. signal to the reactor would give a constant motor torque irrespective of speed. Furthermore, the running of all the motors in parallel would, as explained in the paper, maintain the most effective adhesion characteristics. These advantages alone would seem to warrant a careful study of the possibilities of such an arrangement.

Mr. T. Sealy (*at Newcastle upon Tyne*): Obviously the rectifier locomotives, as envisaged by the authors, are, in fact, 'mobile substations' and quite complicated ones at that, having cooling equipments for transformer and rectifiers, on-load tap-changers, dual-voltage transformers with change-over switches and problems of cold starting, etc. I suggest that the authors should have covered some of the problems of control, metering and alarms to be given in the driver's cab. I assume that the locomotive would be manned by a driver and presumably an engineer, who would, in fact, be a substation attendant. There is obviously a great deal of scope for variation in the control of the various items of equipment, and the ultimate decisions regarding those which are to be automatic and those which are to be manually controlled will require a great deal of thought.

The authors have given considerable thought to the effects of ripple currents on the motors themselves and have considered measures such as the provision of d.c. reactors to reduce this ripple. Unfortunately, they have not give so much thought to the external effects of ripple currents in the catenary, which the addition of reactors would tend to increase. It may well be that the measures which have to be taken to immunize external Post Office plant against the effects of these ripple currents might cost considerably more than the additional equipment required for the locomotive in the way of providing larger motors, etc. Presumably the answer to this problem will not be known until the results of tests being carried out in conjunction with the Post Office are made known.

Mr. H. M. Rostron (*at Liverpool*): One must accept the principle that the ultimate criterion of any form of public transport is reliability, and whilst the use of industrial-frequency alternating current for distribution of power to the locomotive has so many economic and technical advantages, and granted that the system has been fairly extensively tried out in the United States and elsewhere, it appears that the experience gained in the experimental operation of multiple-unit trains in Great Britain leaves wide open many problems that are bound to arise in the large-scale adoption of main-line electrification. For example, the use of high-power locomotives, correspondingly greater load fluctuations due to the fewer, but necessarily larger, substations, and overall, the possibility of outages due to Grid network difficulties and 'out of balance' problems of the 3-phase network. At present, the problems are those for the plant and equipment designers, and the authors must be congratulated for their most comprehensive exposition of the plant maker's proposals.

The stage is now set for the operator. Within the foreseeable future we can expect an integrating paper which will embody the results of actual main-line operation in this country, and furthermore, as the result of experience, the likelihood of large-scale adoption of semiconductor rectifiers and electric braking. Other points, such as track adhesion, axle loading and wheel slip, are major problems which affect the design of locomotives but are obviously outside the scope of the papers, although the authors have explained in some detail the effects of choice of equipment upon track adhesion.

Without in any way detracting from the authors' general statements on design requirements, I am puzzled by a statement in the first paragraph of Section 3.1.4 of Paper No. 2339. For comparable motors of pre-war and post-war construction, namely the types DK32 and EE505, the latter machine with its greatly increased number of commutator bars is far more immune to flashovers than its predecessor, and thus it is a little confusing to read that the motor designer would probably choose a 4-pole motor, with which I agree, but with somewhat less than the maximum number of commutator bars. Perhaps the authors would give their reason for this latter preference.

Mr. J. R. Gandy (*at Liverpool*): I am sure we all agree that the railways should be electrified (20% efficiency for electric traction is better than 5–10% for steam), but why was a 25 kV single-phase and not a 3 kV d.c. system used? Was the decision an economic or a technical one? What is the reason for not liking 50 fixed rectifier substations but not minding 200 or 300 mobile ones of aggregate capacity greater than the required fixed substations, and complete with fixed a.c. substations? A large number of neutral sections will be required for locomotives to transfer from phase A to B or from 6 to 25 kV, the transfer being made without fuss. It is hoped that there will be no failure of the section insulators or relays involved in these hazardous operations. Furthermore, the *present* price of copper must be taken into account.

In Section 3.2.1 of Paper No. 2339 the authors mention rectifiers with a peak inverse voltage of 7 kV. Is it thought that such a high voltage in service could reduce reliability, and would not reliability disfavour the control suggested in Section 3.3.2.2?

I disagree with Section 4.3.1. A very satisfactory multi-anode rectifier has been tested for this duty. In Section 4.3.2 it is stated that, at present, germanium is not suitable. Those who agree with the authors will compliment them on their courage for saying this.

I once heard a speaker complain of 'the mistakes made by non-technical octogenarians of the railways past'. I think that present technical sexagenarians can take heart. With luck they will have retired before it is universally seen that an error has been made.

Dr. W. G. Thompson (*at Birmingham*): Reference has been made to the inadequacy of the infinite inductance theory in dealing with rectifier harmonics.

According to this theory, the amplitude of the current harmonics on the a.c. side varies inversely as the number of the harmonic. I find that dividing these values, respectively, by the successive integers 1, 2, 3, 4, 5, etc., the agreement, although empirical, is in many cases as good as that arrived at by a digital computer. The results are shown in Table A.

Table A

Harmonic	Theoretical value	Empirical value	Measured values	Computer figures
		%	%	%
1	1	1	1	1
3	1/3	16·66	13·7	11·8
5	1/5	6·66	6·2	5·9
7	1/7	3·38	4·1	3·6
9	1/9	2·22	2·2	2·3
11	1/11	1·52	1·9	1·9
13	1/13	0·88	0·8	1·0
15	1/15	0·83	0·3	0·8

The figures in the last two columns were taken from Table 4 of Paper No. 2340; some of the results in Table 5 of the paper show even better agreement. I do not believe that the empirical rule has any theoretical basis except that, over the limited range of harmonics considered, it approximates to the increase in impedance with increasing frequency, and I would not consider it as anything beyond a useful *aide-mémoire*.

Mr. J. G. W. West (*at Birmingham*): In order to make the d.c. traction motor more suitable for operation with pulsating currents, has thought been given to the use of a laminated yoke? The laminations could form only part of the total yoke section, and their main virtue would be to carry the pulsating interpole flux, reducing the angle of lag and the saturation of the magnetic circuit. This would result in improved commutation.

With mercury-arc-rectifier locomotives, is it possible to incorporate regenerative braking, using the rectifiers as inverters, at not too great an increase in weight and cost?

Mr. H. J. Gibson (*at Birmingham*): Presumably the supply for the high-voltage distribution system of the railways will be taken from the 132 kV public supply lines. Could the authors state how far apart the main substations for this purpose would be?

A number of locomotives were constructed with the driving cab in the middle. Is there any reason for this other than economy in space and consequently cost, and does it seriously limit the field of observation of the driver?

In one of the slides shown the locomotive drawing a goods train had only one pantograph erected, although it was equipped with two. Is it usual to use only one pantograph, and are the two pantographs provided each for use in one direction of running?

I am not clear about the authors' explanation of relation between the different adhesion factors and resistance or alternatively transformer tapping control for the motors, assuming the same actual rating. Perhaps the authors can explain more clearly the reason for the difference.

Mr. H. F. Jones (*at Birmingham*): I would like to have further information about the changes which are going to take place in transformer design for locomotives. Mention has been made of the use of high flux densities, and the authors mention other methods for decreasing the weight of such units. Perhaps they can give some particulars of what these are likely to be. I presume they are not worried by the fact that an increase in induction could result in a considerably higher noise level.

The other thing which intrigued me was the mention of the 'nearly normal' d.c. motor. I would like to know the meaning of this expression.

Mr. R. Paterson (*at Birmingham*): The authors describe the advantages of parallel connection of motors during acceleration. In normal operation, I suppose it is unlikely that the series field contactors will be reversed unless the motors are at a standstill, and it may be that interlocking is provided as protection.

From Fig. 1(*a*) or 1(*b*) of Paper No. 2339 it will be seen that, if the series field contactors are reversed before the motors come to rest, very heavy currents will most probably flow between the two motors and may reach short-circuit proportions. This current will flow, even if the power supply from the rectifier is switched off, because very little difference in the characteristics of the motors sets off the current build-up.

In these conditions,* one motor acts as a generator and the other as a motor, the mechanical coupling being direct or by way of the railroad.

Mr. E. Gallizia (*at Birmingham*): In a recent American article dealing with rectifier locomotives, it is recorded that, by the time ten locomotives had been in service one year, each had travelled an average distance of 100 000 miles. It is also stated that only 5% of the original rectifiers had to be removed in the first 1½ years of operation owing to defects. Do the authors consider the figure of 5% replacements to be satisfactory?

Mr. R. S. Winter (*at Birmingham*): The authors refer to the large number of tappings on the transformers. I wonder whether any consideration has been given to some form of infinitely smooth control. I believe that certain schemes have been prepared, and I should be interested to have the authors' views.

Mr. D. H. Tompsett (*communicated*): A matter which appears to be of common interest to both papers is the appropriate representation of the traction motor and its field system. This would ideally be sufficiently simple so that the overall circuit analysis was not made unnecessarily more complicated, while, at the same time, permitting estimation of such quantities as harmonic powers and losses. In what directions do the authors think that progress on this subject will be sought?

The treatment of several trains on a given system is complex, and it is probably that an exact analysis is not required. However, it has been possible to make the suggestions advanced in Section 4.5 of Paper No. 2340 only after the behaviour of a single train could be more rigorously analysed than was previously possible. The treatment of capacitance in the a.c. system may well proceed in a similar way. A practical analytical procedure must first be developed to cater for resonant circuits. This is then available for use with selected examples, from which qualitative conclusions can be drawn about possible effects and measures to be adopted to avoid operational difficulties.

It may be appropriate to refer here to a completely different use of the digital computer for train-timing calculations.* It would appear possible to extend such a programme to the evaluation of substation and circuit loadings. In addition, procedures are available for studying the effects of single-phase loads on the power system. These therefore provide a complete set of computing facilities to handle all the various problems arising in connection with large-scale a.c. electrification schemes.

Messrs. H. B. Calverley, E. A. K. Jarvis, and E. Williams (*in reply*): The following subjects have been referred to by speakers, although it has unfortunately not been possible to include them in the subject-matter of the paper, or in our reply: choice of system; cost considerations; justification of electric braking; locomotive auxiliaries; details of voltage change-over circuits.

Messrs. Phillips and West mention the possible use of inverted operation of the rectifiers to permit regenerative braking. Regenerative braking can be provided in a locomotive equipped with mercury-arc rectifiers. A few German locomotives are thus equipped, but the grid control and inversion may have been chosen in these special locomotives for the precise control of movement at very low speed whilst loading mineral wagons.

Messrs. Bishop, Parton and Phillips refer to stepless control. Saturable reactors, induction regulators, regulating transformers and grid control have all been proposed. Smooth control would increase the mean starting tractive effort obtainable by 5–10% because of the elimination of notching peaks. This might, in some cases, be a sufficient justification, but usually the added equipment for smooth control can be justified only if there is a corresponding reduction in other equipment. A smooth-control device which will itself cover the full range of voltage, with consequent elimination of transformer tappings, is not attractive for one or more of the following reasons:

(i) Worse power factor.
(ii) Reduction in rectifier rating.
(iii) Greatly increased weight.
(iv) Distortion of line current.

* Harwood, P. B.: 'Control of Electric Motors' (Wiley).

* Gilmour, A.: 'The Application of Digital Computers to Electric Traction Problems', *Proceedings I.E.E.*, Paper No. 2113 M, September, 1956 (103 B, Supplement No. 1, p. 59)

The above methods of obtaining smooth control depend for their successful application on being used over a limited range of voltage, say from zero to 30% of full voltage (see Section 3.3.2.2) or between tappings on the main transformers (see Section 3.3.2.1).

Mr. Gandy suggests that grid control or the use of a peak inverse voltage as high as 7 kV might reduce reliability. These factors, and others, are simply a question of each manufacturer's test and service experience, and it is only necessary to work within the limits established by such knowledge.

In reply to Mr. Gibson, resistance control of motor voltage leads to difficulties in regaining adhesion after wheel slip commences. This is because the current of a series-wound motor falls when the wheels slip and hence the voltage drop in the resistor also falls, causing an increase in the voltage at the motor terminals. This makes the slipping wheels attain a higher rate of rotation than if the voltage of their driving motor were rigorously held at the designed value by a specific tap on a transformer.

If the reversers are thrown whilst the locomotive is in motion, but with the power switched off, the dangers referred to by Mr. Paterson could arise with the circuits of Figs. 1(*a*) and 1(*b*), which utilize d.c. busbars, as opposed to the unit system. With such circuits, however, motor contactors would probably be used in each string, and they could be interlocked so that the reverser could not throw unless they were open.

Mr. Brice asks about resistance versus reactance tap-changing. The choice is principally concerned with contactor duty; with a resistor, larger circulating currents are handled but they are at a better power factor, and also some cancellation with the load current is possible with a resistor. If, as is usual, the tap-changing impedance is left in series with the load circuit to obtain running pseudo mid-notches, it affects the efficiency adversely if a resistor and the power factor adversely if a reactor.

The maximum temperature of the transformer windings is 100° C, in accordance with British Standard or I.E.C. Specifications. Messrs. Bishop and Graham refer to class-H insulation, possibly with silicone fluids and closed-circuit gas cooling, respectively, as means of reducing transformer weight. Neither of these methods has been used on 25 kV locomotives, and the former would probably have greater cost and higher losses. With regard to gas cooling, assuming a satisfactory design is possible for 25 kV, a closed gas circuit would be essential for reasons of cleanliness, and it is then likely, as suggested by Mr. Richardson, that the total volume of transformer gear would be appreciably greater than for an oil-filled transformer.

In reply to Mr. Rostron, the tendency of motors to flash over is not directly related to the number of commutator bars but is influenced by the voltage per bar. A motor for a high voltage therefore needs more bars, but one would prefer to use a design with somewhat fewer than the maximum number which can be accommodated in order to be certain of avoiding mechanical difficulties owing to very thin bars.

In reply to Messrs. West, Dunn and Morgan, we would comment that partially laminated yokes have been considered to improve commutation in rectifier-fed traction motors. Their use on actual locomotives, like that of ripple diverts, will continue to be controversial, since neither is essential for satisfactory operation. The ratings given in Table 2 are for a motor in which the main pole flux is allowed to ripple. We regret that inductances for Fig. 18 for currents higher than those shown are not available. With regard to Mr. Jones's expression 'nearly normal' d.c. motor, one way in which a motor fed by rectifiers may differ from a normal motor could be in having its field coils wound for minimum losses (see Section 4.4.1).

The subject of metering and alarm signals to be given to the driver is a detailed matter outside the scope of the paper, and, moreover, the equipment provided varies considerably to suit the particular desires of the operator. With reference to Mr. Sealy's comment, we see no technical reason for the presence of more than one man on the locomotive.

Dr. T. E. Calverley and **Mr. D. G. Taylor** (*in reply*): In reply to Mr. Phillips, since the publication of the paper, calculations have been made for the locomotive studied in the paper, taking into account the capacitance of the contact wire. The beneficial effect of this capacitance on power factor was slightly greater than was expected from a consideration of the nominal charging current of the contact wire; this was due to slight but appreciable changes in the commutating conditions from those which would have existed in the absence of capacitance. The amplitudes of the harmonic currents in the substation output were increased for all harmonics up to the order 27. With regard to filters on the locomotive, the removal of 20% harmonic current would have little effect on the r.m.s. current in the contact wire (the reduction being about 2%), whereas the size and cost of filters on the locomotive would be a serious disadvantage. Any decision to incorporate power-factor correction in the form of static capacitors at the substations would have to be based partly on the usual economic considerations and partly having regard to the possibility of introducing serious resonance problems.

Mr. Richardson's remarks on the last part of the paper provide a qualitative account of the effects of smoothing the rectified current in a resistive load, and indicate the directions in which certain features of performance change as the degree of smoothing is increased. Dr. Thomson's empirical rule for relating the relative amplitudes of harmonic currents on the a.c. side to their order provides a compact summary of this aspect of the results for the particular examples described in the paper. We have found that analyses based on systems simpler than that described in the paper are capable of giving good results for some of the features of performance; such simplifications are not in order if the complete performance is required.

We agree with Mr. Tompsett that the representation of the traction motors is an important part of any analysis. There are two distinct problems involved. The first is the representation of the motors as circuit-elements; this can be deduced from oscillograph records of motor voltage and current, the motor being supplied from a single-phase rectifier. The second problem is to determine how much of the harmonic power taken by the motor is usefully employed in driving the shaft and how much is dissipated as copper and iron losses. This is one factor to be considered when deciding whether to incorporate a resistance divert across the traction-motor field windings.

We would refer Mr. Sealy to Table 6, which shows, for a typical locomotive, the manner in which the harmonic currents in the contact wire change as the inductance in the traction-motor circuit is varied.

In reply to Mr. Gallizia we consider that 5% replacement of rectifiers in the first 1½ years is high, but it must be borne in mind that the figures quoted refer to one of the earliest large-scale applications of rectifiers on locomotives.

DISCUSSION ON 'CATHODIC PROTECTION'*

Before the Mersey and North Wales Centre *at* Chester *28th October, the* North-Eastern Centre *at* Newcastle upon Tyne *11th November, the* North-Western Centre *at* Manchester *3rd December, the* North Staffordshire Sub-Centre *at* Hanley *9th December*, 1957, *the* Northern Ireland Centre *at* Belfast *13th March, the* South-Western Sub-Centre *at* Plymouth *20th March, and the* Western Centre *at* Cardiff *14th April*, 1958.

Mr. L. E. Grant (*at Chester*): My experience of cathodic protection has been limited to Post Office cable plant, which can be afflicted at some unprotected point by all the types of corrosion mentioned in the paper. Bearing in mind that, as a general rule, cables in a telephone area radiate from the exchange building, the most favourable place for the protective rectifier is at this central point. In towns, this is usually in a built-up area. I was therefore surprised by the statement, with reference to anode beds, that there was frequently a wide choice open to the engineer. The reverse is often the case, and the problem is complicated by close proximities to other public services at a point where the cable-to-soil p.d. is required to be at its highest. It is possible to reduce interference by reducing the current output from the rectifier, or it may be possible to change the position of the anode bed so that the current on the other structure is reduced. The connection of the two structures together might be preferable if the foregoing steps are not practicable, and if too much current is diverted, a resistance could be inserted in the connection.

Where some choice can be exercised in the position of the anode bed, the level of the permanent water table and the mechanical condition of the soil cannot be ignored. It is appreciated that a wide variation in its resistance will take place if it is too near the surface of the ground, and the moisture level at the anode is not then stable during the drier months of the year. This is perhaps the best time to explore a possible site for an anode bed, since soil conditions are then at their best and the moisture level is at its lowest point. It has been mentioned that the power cost is almost directly proportional to the resistance of the anode bed, so that time spent on this sort of work is not lost and it can help considerably in obtaining a low-resistance connection. A geophysical ground-exploration method could be usefully employed for this purpose where the circumstances are favourable, or tests with deep-driven rods might be enlightening. Either or both checks are likely to be cheaper than setting up generating equipment to obtain test results after an anode bed has been provided.

I find Fig. 3, and the statement that a single installation could protect from 20 to 50 miles, very attractive. I compare it with the very shallow curve obtained on an unprotected cable and the fact that an output of 5 amp under some circumstances would not produce a noticeable change in potential at a point of about 1½ miles from the protecting rectifier. These extremes are interesting. It does show that it is economically advantageous to provide a protective wrapping when opportunity permits, if it cannot be provided at the outset, so that current consumption can be progressively reduced as the area of protection is increased.

Mr. J. H. Gosden (*at Chester*): Even if the water resistivity is low, I do not agree that reactive anodes are preferable to the impressed-current method. Tests carried out at power stations show that the current required is frequently higher than could readily be obtained from reactive anodes. An important point in the case of high-efficiency plant is that a long anode life is necessary to avoid unnecessary shut-downs. This could best be obtained by using the impressed-current method with anode materials, such as graphite, which do not corrode. Economically this method alone is generally better than protection by coatings or a combination of coatings and cathodic protection.

Mr. G. W. Galley (*at Chester*): Our first experience with electrolytic corrosion protection concerned a multi-cored telephone cable 170 yd long, bare-lead sheathed and laid in ground known to be impregnated with caustic material. This cable failed twice in rapid succession, displaying characteristic electrolytic corrosion. A magnesium sacrificial anode was installed at each end of the cable and no further trouble has been experienced for five years.

The second example relates to a 250 ft length of 200-pair telephone cable, lead-sheathed and served, and laid in ducts under a public road. One year after laying, the cable failed and examination showed extensive corrosion at one end only. The damaged end was cut off and replaced but failed again in a similar manner 18 months later. The cable was then replaced in its entirety and fitted with two magnesium sacrificial anodes. Since then, the cable has lasted nearly four years without further trouble.

Our experience of water-pipe protection concerns a mile length of 12 in steel main, bitumen coated inside and out, which developed four bursts within 12 months over a length of 60 ft. Although the soil at this point appeared different from elsewhere along the route, chemical tests revealed no local abnormality. Two anodes were installed to cover the vulnerable length, and for two years since only one burst has occurred. Consideration was given to protecting the entire pipe, but the cost of finding the pipe joints and bonding across them was not considered justifiable.

Since many patent joints for water mains do not offer electrical continuity, it may be advisable always to bond across such joints when laying mains to facilitate future protection.

Mr. A. E. Bishop (*at Newcastle upon Tyne*): The authors make no comment on troubles arising from a.c. electrolysis. Information seems somewhat scanty, and I should be glad to have the author's views. In cases where this does occur, can cathodic protection be applied?

Mr. J. Tozer (*at Manchester*): Section 4.3 mentions the coating of pipe lines, but does not give any details of the type of coating or the electrical resistances which are obtainable. I should be glad if the authors could give these details.

The importance of care in handling coated pipes cannot be over-emphasized, and particular attention should be given to ensuring that the backfill does not include rubble that could pierce the coating. It would be interesting to have more details of the tests carried out over continuous lengths after installation.

In Section 5.2 mention is made of reducing to the lowest practicable value the resistance to remote earth of the anode bed. Could the authors explain what methods are used for this?

* Hobgen, L. B., Spencer, K. A., and Heselgrave, P. W.: Paper No. 2336, February, 1957 (see 104 A, p. 307).

With regard to measurement using half cells, what is the approximate potential developed at the junction between the solution and electrolyte?

I understand that in America a silicone-alloy anode is being used which expends less than 1 lb of metal per ampere per year in comparison with 20 lb of metal per ampere per year when using scrap iron or steel. Could the authors state whether it is being used in this country?

I believe that bonds between steel and concrete in foundations can be weakened if an excess current is passed through them. Could the authors give the maximum level of current density to avoid this?

Mr. G. F. L. Dixon (*at Manchester*): The remedial measures necessary to prevent accelerated corrosion in neighbouring metalwork can be as important technically and economically as the design of the protective scheme itself.

A protective scheme is being applied to a 27-mile pipe line as the first stage of protecting a 130-mile high-pressure gas Grid in North Wales. At 128 points along this 27-mile section, electricity supply cables cross or lie near the pipe. To carry out the prescribed potential-swing tests, five test teams worked for a week. Of the 128 points, 63 were found to be endangered by the proposed scheme.

The following conclusions were drawn: Individual swing tests over the remainder of the 130-mile route would be uneconomic. Tailor-made remedial measures applied to individual points were out of the question, solid bonding at crossing points and proximities being the only practicable solution.

If one adopts solid bonding for such large schemes, it seems logical to adopt it for small ones. There are many more of them, and we should be saving a considerable volume of expensive testing and other work. It seems likely, in fact, that we are entering a period when solid bonding will be the rule.

The designer of protective schemes will not then be able to work in isolation, but will have to plan the size and disposition of his anode beds only after he has plotted the positions of all the bonds that will be needed. In certain cases, because of the extra current necessary, protective schemes may be considerably more expensive to the organizations applying them than they are now.

Lieut.-Col. F. A. Richmond (*at Manchester*): It is possible to protect not only the outside of containers such as tanks from corrosion from the soil, but also to protect the inside of vessels from corrosion from the contents. I wonder whether work has been done to prevent corrosion on the inside of tanks containing corrosive chemicals. Is it possible to develop this system in order to reduce the corrosion of the inside of pipes carrying corrosive chemicals, and to extend the idea of cathodic protection to pipes carrying corrosive gases?

Mr. H. S. Jones (*at Manchester*): I feel that Sections 9 and 10 have been over-simplified. In our experience in the gas industry, interference can be a very serious problem in the application of cathodic protection—so serious at times as to render this type of protection difficult to apply successfully.

I need not elaborate on the extreme congestion of underground plant in this country, and this problem of interference can not only be severe from an application point of view, but it can also be very difficult to trace. I am sure that the authors will agree that the more difficult the interference is to trace, the more serious is the effect likely to be, owing to the probability of extreme localization. This difficulty is more pronounced on impressed-current systems where the power input is higher than on sacrificial-anode systems. However, as shown in the paper, sacrificial anodes can be used only where the soil resistance is comparatively low or where the current requirements are small. What do the authors consider to be the likely solution to this dilemma? If impressed-current systems are used to any extent in this country, interference effects are likely to be far-reaching in character and possibly serious in consequence, whilst if sacrificial anodes are employed, we shall, in effect, be developing a system which is not entirely suited to the conditions under which they are required to work.

Mr. R. J. Gent (*at Hanley*): There is very little reference in the paper to power cables. Perhaps the authors could comment on their experience in this field.

It is stated that current requirements can vary greatly (see Section 4.1), and if bonding is adopted, it is understood that the current output of the anodes or rectifiers must be increased by the amount diverted to the neighbouring structures. I am interested in a network of many miles of power cables already bonded together. What practical difficulties, if any, might one expect to encounter if it is agreed to bond to the equipment of another undertaking adopting cathodic protection?

With regard to testing, the authors give no information on the high-resistance moving-coil voltmeters or potentiometers required, and they have not referred to the Joint Committee for the Co-ordination of the Cathodic Protection of Buried Structures.

The Area Boards do not have underground-cable inspection boxes to the same degree as the Post Office. To help in periodic testing, would the authors advise bringing a connection almost up to surface level from the lead sheath of a power cable and recommend that a small inspection chamber be used with a lid similar to a normal house-service water-tap cover plate? How often do the authors suggest that routine testing should take place?

Experience has shown that there is only little trouble with corrosion on power cables in the Stoke-on-Trent area. However, on the last occasion I remember it was rather serious, and occurred on 6·6 kV single-core 1 in^2 cables not protected by serving. The damage may have been caused by local cell action in which parts of the cable sheath acted as anodes and parts as cathodes, rather than by direct chemical action with the clay which surrounded the cables.

Mr. T. Williams (*at Hanley*): The low incidence of corrosion faults on power cables limits our experience to the interference aspects of the paper.

In Section 9 the interference effect is summarized without explanation. The potential swing will depend on which part of the installation is in proximity. The anodic swing which results from the structure being near a protected pipe is simple enough, but when the swing results from a ground bed or anode, the local effect is cathodic and we must start looking elsewhere for the point where current leaves the structure. The anodic effect can then be measured. This can be the most costly side to interference testing.

Too often, engineers at District level have no other reference beyond that of giving supply to a rectifier, and we have already experienced the case where substation and neutral earths were laid almost direct in an anodic ground bed.

In Section 9 the authors state 'The simplest way . . . is to bond'. With most structures bonding is indeed simple, through cartridge welding or clamps, but, with possible fault conditions, we insist that both lead and armour are plumbed in power-cable bonds. A single bond may occupy a jointing team for one day. If two or three cables involved in interference are already bonded at the substation, in our experience separate bonding is still required in the protection area. In this locality impregnated gas pressure cables are standard for 33 kV, and in the event of bonding, cast plumbs would be required. Consequently I am not happy with the word 'simplest'.

In Section 11 the authors suggest that power cables should be

bonded to other structures via water mains. I am not sure whether power engineers will support this suggestion. In the past we have insisted that separate bonding be employed.

Mr. J. Wainwright (*at Hanley*): The term 'power-impressed cathodic protection' could almost be used as one way of describing the electro-osmotic method of soil stabilization in civil engineering. Here, direct currents, often in the region of thousands of amperes, are passed between electrodes buried in the soil, with the result that water is transported to the cathode and the soil becomes more stable mechanically.

My interest in this matter relates to the movement of moisture in dielectrics under the influence of electro-osmotic forces which result from the passage of leakage currents of the order of micro-amperes. I should be very interested to learn whether the authors have found evidence of the transport of water to the cathode in the plants with which they have been associated. In certain soils, this feature could presumably have quite a nuisance value, since certain parts of the site could become waterlogged.

No information is given in the paper on the performance of the various coating materials, and I should like to know whether the authors have had any experience with the comparatively modern glass-fibre epoxy-resin type of covering.

It would be interesting to know whether submarine cable sheaths are subject to corrosion, particularly now that high direct voltages are being transmitted with earth return via salt water.

Mr. M. L. Gorham (*at Hanley*): The C.E.G.B. Panel charged with considering cathodic protection is at present very actively engaged on the two principal points that arise out of interference from protected installations, namely bonding and indemnity of the owners of the foreign structure.

The danger aspects of bonding to power cables when fault conditions arise, in spite of the arguments put forward, can, under a combination of circumstances, be very real, and theoretical consideration of the distribution of fault current in the ground surrounding a buried pipe is a very complex study. The prediction of results based on past experience is rather like the prediction of effects of cathodic protection. The circumstances of each separate case must be considered, and no generalization can be applied.

In consequence, the Panel is pressing wholeheartedly for the adoption of a national form of indemnity. The Midlands Electricity Board has already signified its intention of supporting the document when it emerges. In the meantime, we are bonding without such indemnity in the belief that the functional documentation of the science will, as always, eventually catch up with the engineering practice.

Mr. W. Szwander (*at Belfast*): While it may appear surprising that, despite immense financial losses incurred everywhere through corrosion of metals, the principle of cathodic protection, so simple in its essence, has until now found comparatively little application in practice, I can see the following two main explanations for this. First, though the theory of cathodic protection is straightforward and well understood, its quantitative application is entirely dependent on empiricism and effective protective metal-electrolyte potentials or densities of impressed protective currents obtained from practical experience. As over-protection has its own disadvantages, both technical and economic, and under-protection may make the whole application of protection of rather doubtful value, the difficulty is obvious. Particularly when protecting one metal immersed in an electrolyte, there are no theoretical clues as to the desirable levels of protection; but when full inspection is occasionally possible, we can determine the effectiveness of protection before irreparable damage has actually set in. The second very serious difficulty is that of dealing satisfactorily with the dangers of interference. While the bare cost of providing cathodic protection itself in the vast majority of cases can be justified economically without any difficulty, the cost of investigating and counteracting the possible effects of interference may be quite unpredictable, and hence the economics of the whole venture may be doubtful and impossible to assess in advance. This is quite apart from the equally unpredictable, but usually considerable, difficulties and waste of time in achieving any finality in the proposed scheme.

I am interested in applying cathodic protection to high-pressure steel pipe lines of a high-head pumped-storage scheme working on sea water. Long useful life of the pipes and the necessity to be absolutely certain that their mechanical strength will not be impaired by corrosion would require a high degree of certainty as to the cathodic-protection effectiveness. Presumably protection of both the internal and external pipe surfaces would be required with protective anodes immersed both in sea water circulating through the pipes and in the soil in which the pipes (or tunnel linings) are buried. No interference difficulties would be anticipated in respect of the internal protection, but external protection might present some considerable difficulty. It would be very interesting to know the authors' experience of similar applications.

Mr. N. C. C. de Jong (*at Belfast*): The formula in Section 4.3 is correct only if the anode is sited over 100 yd from the system it protects. Most anodes are well within that distance, and the effect of the potential gradient they set up in the ground bed and surrounding earth is an increased negative potential along the structure for distances of up to a quarter of a mile in each direction.

The critical point for testing for interference effects to an adjacent cable or pipe is not at its nearest point to the protected structure, but up to a quarter of a mile away, where any interfering currents may be leaving to return to the anode; bonding at such points is often more difficult and costly, and the change in potential due to bonding between different metals must not be overlooked. The limit of 2·5 volts mentioned in Section 8 is considered to be most conservative, and latest tests indicate that up to 10 volts could be tolerated without risk of damage to coatings or wrappings.

The Post Office practice is to bring all earth rods to a central inspection chamber and make all connections there with p.v.c.-covered wire. The development of these techniques is urgently required, but may have been held up for years because of natural fears of interference to other services involved.

In view of the work of the Joint Committee for the Co-ordination of the Cathodic Protection of Buried Structures, the care taken in testing, and the new techniques in bonding, it was hoped that the application of the method to the telephone network in Northern Ireland would be helped by all concerned.

Mr. A. G. R. Bell (*at Plymouth*): The electricity supply industry suffers severe corrosion in its sea-water-cooled power stations. During the last few years thorough investigations have been carried out on methods of protection, and results indicate that impressed cathodic protection is not the most economical.

The main interest has been the protection of metals in the cooling-water systems of large turbo-alternators. With regard to main condensers, sacrificial plates of wrought iron were used to counteract dezincification of the brass and build up a protective coating in the brass interfaces. This was not very successful in sea- or estuary-water sites, and so corrosion-resistant alloys were used, for example cupro-nickel, Yorcoron and aluminium-brass. These materials readily acquire a protective coating, but the cast-iron water boxes suffer graphitic corrosion.

This cast-iron attack is so severe that a 1½ in thick casting has perforated in five years. Experience has shown that corrosion

is accelerated by the essential presence of non-ferrous metals in the cooling systems.

Protection of these boxes on post-war plants is a major problem. Experiences at Plymouth 'B' and East Yelland are given below:

Originally, cathodic protection was installed on all condensers at Plymouth to protect the tube plate and tubes from corrosion, but the process was shortly discontinued on the following counts:

(i) Aluminium-brass forms a better film without impressed currents.

(ii) Cast-iron anodes rapidly disintegrate, causing tube blockages and high anode-replacement cost.

(iii) After six months' operation there is ineffective protection of cast-iron water boxes against graphitization.

Cathodic protection was abandoned, the water boxes were dismantled, sand-blasted and the exposed surfaces were coated with synthetic rubber. On reassembly the boxes were insulated from the tube plate and connecting pipework. This proved effective, and five condensers installed are satisfactorily protected. The sixth had cathodic protection recommissioned with the following modifications: The anode materials were changed to impervious graphite and satisfactory anode positions were established. Anode currents were adjusted to 1 amp per anode on the return end and 1·5 amp on the inlet and outlet end—14 anodes each end. During a 15-month trial, complete protection was given. All surfaces were coated with magnesium carbonate. The anode life is expected to be approximately three years, against three months with cast iron. On a cost basis, synthetic rubber is more economical.

Cathodic protection, capital cost .. £900 (1950)

	£
Interest and depreciation	90
Power cost	27
Anode renewal	24
Maintenance	15
Total annual	156

The cost of synthetic rubber, including the original preparation, is £455, with an expected life of six years, giving an annual cost of £76. The renewal cost is estimated as £300, giving £50 future annual cost.

Experiments were carried out at East Yelland with fully-coated water boxes and cast-iron sacrificial anodes, which caused tube failures. Wrought-iron anodes, however, proved satisfactory. One condenser water box was unprotected, but fully insulated. After six months, graphitic corrosion had penetrated to a depth of $\frac{1}{8}$ in.

A cast-iron water box for a 30 MW condenser, with a life of 10 years, costs approximately £9 000 excluding labour costs, etc. The pumps and valves are subjected to similar corrosion attack. Bronze valve seats, impellers, sleeves and sealing rings are now replaced by stainless steel or cast iron in coast and estuary stations. Impressed cathodic protection is almost impossible to apply to these parts and protective coatings are ineffective.

Cast-iron pipework is another field for research; the interior surfaces requiring protection would probably entail a continuous anode situated at the pipe centre. This raises mounting and replacement difficulties.

I agree that cathodic protection is an extremely wide subject, and its application calls for a careful survey of each individual case. The application of sacrificial or impressed cathodic protection is a matter for the specialist.

Mr. W. Hill (*at Cardiff*): No one can dispute the fact that cathodic protection has proved of great benefit and effected real protection in a great number of cases. The theory is obviously sound, but the claims made for the system and the accuracy of the formulae are often to be disputed.

In some 19 cases carried out in recent months it was found, on comparing the demand which was called for and the actual loads taken, that they varied from an increase by a factor of 1·7 to a reduction by a factor of 26·8, i.e. 1·1 kW to 41 watts. However, the original demand included such figures as 1·64, 1·27 and 2·04 kW, which led one to expect accuracy. There is a great difference between theory and practice, and these figures have not been remedied even after the time allowed for polarization.

It may be that insufficient notice was taken of the full geological formation, in that there was not only a change in geological formation through which the pipe passed, but the sub-layers varied considerably and at various depths. Furthermore, the formula does not seem to take enough account of the varying features, because there is not only the geological formation, which probably governs the soil resistivity, but also bacteriological and galvanic actions, which may involve wide discrepancies apparently impossible to calculate.

The cost of providing supplies for these installations varied from a simple service to £786. It must be obvious that the very low power—under 100 watts—cannot be applied economically if the capital cost is to be £700, and in these cases, a further investigation with the idea of using the wasting-anode method would be better.

With regard to interference with other structures, records have already been obtained showing that, even with loadings of 84 and 118 watts, it has been necessary to bond to other cables. In my knowledge a wasting magnesium anode has given sufficient potential on adjacent cables to call for bonding. This may be of interest, since it has been claimed that only in the higher-power cases would bonding ever be necessary.

It is doubtful whether real benefits can be achieved in towns, since there seems to be a definite tendency for higher powers to be required after bonding, and then for more bonding to be necessary. While one case in Belgium may appear to be successful, I wonder whether it will be confirmed in years to come.

Mr. W. T. Malson (*at Cardiff*): Since the authors state that the maximum anodic shift permissible on a buried structure is dependent upon whether or not sulphate-reducing bacteria are present in the surrounding soil, I would welcome their comments on (i) how the presence of such bacteria may be determined on site, and (ii) the maximum anodic shift they would be prepared to accept on an underground h.v. power-supply cable under such circumstances.

In the film I noticed that, as a result of a circular disc of a particular material being rotated at speed in a salt-water solution, corrosion took place on its periphery. I was particularly interested in this phenomenon, since I know of a number of high-speed high-pressure turbine pumps where the metal insert on the balance disc and the mating rings on the fixed portion of the pump are failing in service, as a result of partial fractures after only a few hundred hours' operation.

Although this matter is being thoroughly investigated by the pump manufacturers, with a view to overcoming the difficulty, I should be interested in any comments the authors could make on this form of failure, bearing in mind that the metal insert on the balance disc is 18/2 chrome-nickel stainless steel, and that the mating ring on the fixed portion of the pump is monel metal.

Messrs. L. B. Hobgen, K. A. Spencer, and **P. W. Heselgrave** (*in reply*): We agree with Mr. Grant's remarks about anode beds in the case of Post Office exchanges in built-up areas, namely that the choice of site for ground beds is normally very restricted. Yet, in general, for cathodic-protection schemes there is quite

a wide choice, and it certainly pays to explore the ground carefully before making a final decision. It is agreed with Mr. Gosden that power-impressed cathodic protection is finding increasing application to cooling systems using sea water. There is still some doubt as to the economics (see Mr. Bell's contribution). Mr. Galley's experiences are noted with interest, and we endorse his remarks on bonding. In reply to Mr. Bishop, we know several cases of rapid corrosion attributable to electrolysis. These have usually been associated with d.c. traction systems when using an earthed running track for the return current. This effect can generally be eliminated by the installation of one or more polarized bonds. This practice has been extensively adopted on the Continent, notably in Belgium.

The omission of pipe-coating details was entirely due to lack of space. The best economic type of coating is probably hot applied coal-tar or petroleum-asphalt-base enamels reinforced with glass-fibre wraps. The insulation resistance when first installed is very high but varies so much with the actual wrapping used, its thickness and the site conditions, that it is impossible to give a value that has any real meaning. The important criterion is the current required to give protection. It is this current, compared with the value obtained from a knowledge of the pipe length and diameter, and the current per square foot, which should give adequate protection to well-coated pipes in similar conditions, that form the basis of tests after installation. To reduce the resistance to remote earth of the anode bed, (i) it is necessary to site the ground bed in that part of the available ground which has the lowest resistivity over the whole year, (ii) the size, number and spacing of the anodes must be the best for the particular site and current requirements, and the current density should not exceed 1 amp/ft^2, and (iii) it is necessary to consolidate the fill round the anodes very thoroughly. The potential at the junction between the electrolyte and the copper-sulphate solution of the half cell is about 10 mV.

The high-silicon alloy anode (12–15% silicon) used in America has been used in this country for some considerable time, and the figures quoted by Mr. Tozer are substantially correct. It is true that bonds between concrete and steel reinforcement can be weakened if current is passed to the steel through the concrete, which is not completely impervious to moisture. We have little experience of this matter and would refer Mr. Tozer to the E.R.A. Report.*

There is a good deal in what Mr. Dixon says about the time and expense taken up in testing the results of cathodic protection in neighbouring structures. The designer of protective schemes should not work in isolation but should take into account all the underground structures likely to be affected before he decides on the location of his ground beds. It is, of course, very probable that some structures will be missed on an extensive scheme, but conditions are rarely as bad as Mr. Dixon envisages.

Lieut.-Col. Richmond is informed that work has been done to prevent the corrosion on the inside of tanks and pipes carrying corrosive chemicals, but normally it is cheaper to use more corrosive-resistant material. Since cathodic protection is only effective in the presence of an electrolyte, it is not applicable to prevent corrosion by gaseous materials.

It is agreed with Mr. Jones that Sections 9 and 10 are over-simplified, but this is inevitable in a short general paper. There are cases where sacrificial anodes and power-impressed currents can both be used on the same scheme with satisfactory results. The whole question of interference is being continually reviewed by the Joint Committee for the Co-ordination of the Cathodic Protection of Buried Structures, and it is hoped that some simplification of the testing routines will be evolved in the not-too-distant future.

We have little experience with the direct protection of power cables in this country, as the number of such schemes is small. However, there are many cathodic-protection schemes which affect power cables, and these have been dealt with as they arose. Mr. Gent's query on the practical difficulties that might arise if he agreed to bond his system to another undertaking adopting cathodic protection is too general to be given a definite answer. With regard to high-resistance voltmeters and potentiometers, Mr. Gent is referred to the catalogues of instrument makers who specialize in such equipment for cathodic protection. We should recommend inspection chambers as Mr. Gent suggests, and tests should be made at least annually, but better still every six months.

Mr. Williams points out that bonding may not be simple. We stated that the simplest way of eliminating an undesirable effect was to make an electrical bond, not that bonding was simple. Actually, most bonding is fairly simple, but the special case of h.v. cable is not so easy and is, of course, quite expensive. We suggest that often all that is required is a bond from the protected structure to the cable armouring, although it is agreed that local bonding will probably be required in addition to bonding at the substation. In reply to Mr. Wainwright, we have so far not found any evidence of the transport of water in quantity to the cathode due to the cathodic protection currents, but water movement will undoubtedly take place, although it is very unlikely to cause any part of the site to become waterlogged. The movement of water away from the anode by this mechanism may cause a substantial increase in ground resistance. Submarine cable sheaths near the shore are armoured and subject to corrosion, and can be cathodically protected. However, the deep-sea part of the cable is not affected by the high direct voltages used for the repeaters, in spite of the sea return, owing to the cable to the repeaters being exceedingly well insulated by a ½ in polythene cover.

The question of indemnity mentioned by Mr. Gorham is being discussed at national level and does not call for comment here. In reply to Mr. Szwander, we have had considerable experience with the cathodic protection of high-pressure steel pipe-lines working with sea water, and both internal and external protection has been achieved. Mr. de Jong is not quite correct about the formula in Section 4.3. This assumes a remote ground bed. The limit of 2·5 volts for the metal-electrode potential is conservative, and in some cases much higher values have been used.

Mr. Bell's contribution is very interesting and instructive. Condensers for turbo-alternators using sea-water cooling have, however, been successfully cathodically protected. Mr. Hill's experiences have been a little unfortunate. It seems that insufficient care must have been taken with the initial investigation and tests. Of course, variations of power will occur, chiefly owing to the soil resistivity varying throughout the year, and often adjustments have to be made after the ground beds have been installed, but, in general, the variations noted and adjustments required are of a minor nature. Cathodic-protection schemes were initiated in Belgium in 1933.

In answer to Mr. Malson, (i) the presence of active sulphate-reducing bacteria in the soil should be suspected if the ground is waterlogged clay. Their actual presence can only be proved by taking samples of the suspected soil and making cultures in nutrient solution in the laboratory; (ii) the anodic shift we would be prepared to accept on an underground h.v. power cable with fully active sulphate-reducing bacteria in the soil would be 10 mV as a maximum. This value is under constant review by the Committee.

* Mole, G.: 'Electrolysis and the Bond Strength of Reinforced Concrete—Effect of Direct Current' (E.R.A. Report Ref. B/T6; 1949).

DISCUSSION ON

'SOME ASPECTS OF HEAT PUMP OPERATION IN GREAT BRITAIN'*

NORTH MIDLAND UTILIZATION GROUP, AT LEEDS, 19TH NOVEMBER, 1957

Mr. J. G. Jagger: There are two particular aspects of the paper on which I would like to comment: first, the use of electricity generated from heat in a central power station for driving a heat pump, and secondly the consideration of sources of low-grade heat for utilization in this way.

The first is not independent of the second, since reference is made in the paper to condenser cooling water as a source of heat and to the controversial views on this point. The energy abstracted from the heat at the station during a fall in temperature below that at which heat is required must be returned to it at the pump to restore the temperature. In using this kind of electricity, therefore, in comparison with energy generated from water power, or generated locally with its rejected heat at the required temperature additionally available, it might be reasonable to assess its cost on a thermodynamic cycle whose lower temperature was that of the required heat and using heat sources naturally available.

With regard to the availability of low-grade heat, one cannot help but feel that, if it is not delivered gratuitously to the pump by moving water or air, there is indeed no prolific source of this kind. In the installation described the heat is only provided at the cost of a substantial fall in local ground temperature. Since the heat in question is radiation from the sun passing into the ground, the suggestion is made that it might be collected more directly in a manner similar to those described by Dr. Heywood† in his recent lecture on solar energy. A combination of the two arrangements might well result in successful operation.

Perhaps the most promising field for the heat pump is the illustration given of the compressor evaporator. In this case the end product is not, in fact, heat but a distilled liquid, and the purpose of the pump is to step up the temperature by a relatively small amount at one point in the cycle. This leads to a high performance ratio, and there is no difficulty with regard to a heat source, since little is required from outside the system. It is not unreasonable to suggest, therefore, that, where a building is to be heated by a pump, the scheme should include adequate heat insulation and other loss prevention, when a combined heat exchanger and pump would return the exhausted heat through a small temperature range with high performance and minimum difficulty with regard to the heat source.

Mr. F. R. Harrison: The author gives the impression that it is in the domestic field that the greatest development of the heat pump can be expected, and mentions that fractional-horse-power units show the greatest promise.

I am not certain that the development of the heat pump in the fractional-horse-power range is the best line that can be taken, and in my view, for the time being, it would be best to obtain information on heat pumps used in a higher-capacity range, particularly in those cases mentioned by the author where favourable conditions may exist.

I am aware that, up to the present, it is only in the domestic field that an attempt has been made to produce and market a packaged heat unit, and, moreover, the machine is driven by a fractional-horse-power motor. It appears, however, from experiments which we have carried out with this machine, which is a combined water heater and larder cooler, that it will be difficult to get satisfactory results from a machine of this size.

Nevertheless, we should be grateful to this particular manufacturer for, at least, attempting to do something practical in the way of developing the heat pump, and although I am pessimistic about their chances of achieving any great success, I shall be very glad if this pessimism proves to be unjustified. Their efforts are also showing that, from an engineering point of view, the quantity production of a domestic heat pump of some kind is a reasonable proposition.

In my view, the satisfactory development of the heat pump for domestic purposes will come about only if a unit of such size that its output is high enough to heat the greater part of a normal house is used, and also if the refrigeration aspect is ignored.

Miss M. V. Griffith (*in reply*): In reply to Prof. Jagger, the economics of the use of power-station cooling water as a heat source for the heat pump is best kept on a severely practical level, since any theoretical treatment is very dependent on the actual conditions which can be utilized in practice. Comparative tests against other methods of heating similar buildings, taking all contributing factors into account, provide the only satisfactory yardstick.

It is quite true that the use of the ground as a heat source is an indirect method of using solar energy. It must be remembered, however, that the ground forms a heat store for a considerable part of the aggregate solar radiation of the summer, and this storage would be expensive to provide otherwise. A combination of the two methods has been considered and is to be tried at the first opportunity.

Prof. Jagger is probably right in his assessment of the potentialities of the thermo-compressor or process heat pump. The difficulty about using the method of direct up-grading of exhausted heat or space warming, however, is the amount of fresh air people need. Nevertheless small room units used as suggested have been made and operated with a p.e.r. of 4. It is essential to minimize noise with these small local units, and the solution may lie in alternative methods utilizing no moving parts, e.g. thermo-electric heat pumps, a lower p.e.r. being accepted.

In reply to Mr. Harrison, the reference in the paper to the domestic field as that of greatest promise is concerned mainly with the number of units which could be employed and not necessarily with technical success. It is also stated in the conclusions that the best hope in this country is the utilization of favourable heat sources.

The marketing of a package heat pump in Great Britain has, however, introduced a wide public to the potentialities of this method of heating, and although I agree with Mr. Harrison that units large enough to provide central heating are preferable, it has not yet proved possible to persuade any manufacturer to proceed with these in quantity because of the purchase tax. The recent reduction in this may prove helpful.

The performance of the hot-water units could be improved

* Griffith, Miss M. V.: Paper No. 2273 U, December, 1956 (**104 A**, p. 262).
† Heywood, H.: 'Solar Energy for Water and Space Heating,' *Journal of the Institute of Fuel*, 1954, **27**, p. 334.

somewhat if the refrigeration aspect were ignored, but the provision of this facility is a selling point, and should be charged for, at least at the rate of 25% of the maximum possible cost of running a larder heat pump, namely that associated with the use of 80 kWh per week. The normal consumption in practice is considerably less than this, especially in summer, but the effective p.e.r. does, of course, vary with the quantity of water used.

WRITTEN DISCUSSION ON 'AN EXPERIMENTAL APPROACH TO THE COOLING OF TRANSFORMER COILS BY NATURAL CONVECTION'*

Mr. J. van Bueren: The authors have ignored the effect of the thermal conductivity of the coils in the vertical direction. For the simple coil structure used in the tests, if q is the rate of heat

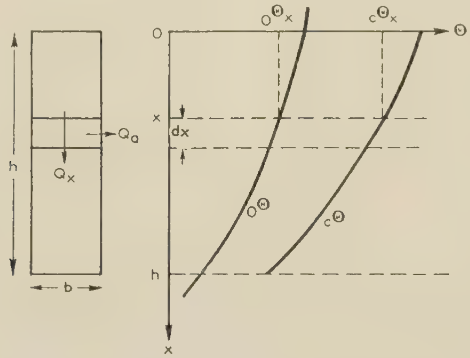


Fig. A.—Oil and copper temperature distribution.

$_0\Theta$ = Oil temperature.
$_c\Theta$ = Copper temperature.
Q_x = Heat flux density in axial direction.
Q_a = Heat flux density in radial direction.

generated per unit volume and P is the heat flux (Fig. A), then, assuming no circumferential heat flow,

$$P_x = Q_x b = -\,bk_x \frac{d(_c\Theta_x)}{dx}$$

$$dP_x = -bk_x \frac{d^2(_c\Theta_x)}{dx^2} dx$$

and $$P_a = Q_a dx = f_c(_c\Theta_x - {_0\Theta_x})$$

now $$qbdx = dP_x + dP_a$$

hence $$k_x \frac{d^2(_c\Theta_x)}{dx^2} - \frac{f_c(_c\Theta_x - {_0\Theta_x})}{b} + q = 0$$

If the first term is zero ($k_x \neq 0$), $_c\Theta_x$ varies linearly with x. This condition is not fulfilled near the base of the open coils, where $d^2(_c\Theta_x)/dx^2$ is large, but is approximately true for the remainder of the coil.

There is in addition a helical flow of heat along the conductor. This can usually be neglected, but it may influence the thermal distribution when the conductor section is large or when a large number of conductors are wound in parallel. The effects, on the thermal distribution, of axial and helical heat flow are more important when the outer surface of the coil is insulated.

For these reasons, the method described in Section 4.3 to determine f_c is inaccurate, especially for values near the base and top of the coil. This conclusion is confirmed by Fig. 5, where maximum values of f_c occur at positions having the lowest oil temperature and velocity, and this is contrary to expectation.

Presumably, to provide a consistent representation for different dissipations, the temperature distribution curves of Figs. 3 and 4 have been adjusted for a given ambient air temperature. The authors have not stated whether this is the case, and if so, the method employed. A full understanding of the temperature distribution is only possible with a knowledge of both the ambient temperature and, by curves, the oil temperature distribution over the entire oil height.

The irregularities in the curves of Figs. 4 (*c*), (*f*) and (*j*) appear to be due to the transition from laminar to turbulent oil flow.[16]

With open coils, oil can collect from the oil bulk to join the oil stream at the coil face, the flow being appreciably greater near the top of the coil than near the base. If ducts are fitted to the coil, oil collected along the coil surface must enter the duct at the base of the coil. The oil flow through a duct is usually laminar or turbulent along the entire coil height.

The application of Grashof's number to the laminar flow region, taking as the characteristic dimension the height of the maximum oil temperature above the coil base, gives consistent results for the work of various investigators. The authors' curves for open coils also give good correlation, but there is no agreement for coils fitted with ducts. It may be that the irregularities in the curves for ducted coils are points of inflection, and consequently the shape of the upper parts of these curves requires further investigation.

There is a marked difference in behaviour between unilaterally heated ducts, as in the experiments described, and those heated bilaterally.

The authors may be commended for giving the relation between the copper-to-oil temperature difference and the surface heat dissipation in terms of the surrounding oil temperature. The relation is, however, affected by the temperature distribution along the surface, surfaces having a uniform temperature behaving in a different way from the normal coil surface in a transformer. This variation of surface temperature, which is a function of the axial heat flow, creates complications when attempting to provide a correlation between Nusselt's number and the product of Grashof's number and Prandtl's number.

Mr. P. H. G. Allen: Forty-seven years ago, Weed[A] emphasized the need for detailed study of each separate step in the total transformer temperature gradient, and the authors are to be congratulated on following this excellent precept. However, the system they have isolated differs somewhat from the actual thermal system represented by a layer-type winding. A vertically aligned annulus has, in any horizontal plane, a most desirable uniformity of heat-transfer characteristics. In a layer-type transformer winding, on the other hand, the annular space between layers consists only partly of liquid coolant and the

* Taylor, E. D., Berger, B., and Western, B. E.: Paper No. 2505 S, April, 1958 (see 105 A, p. 141).

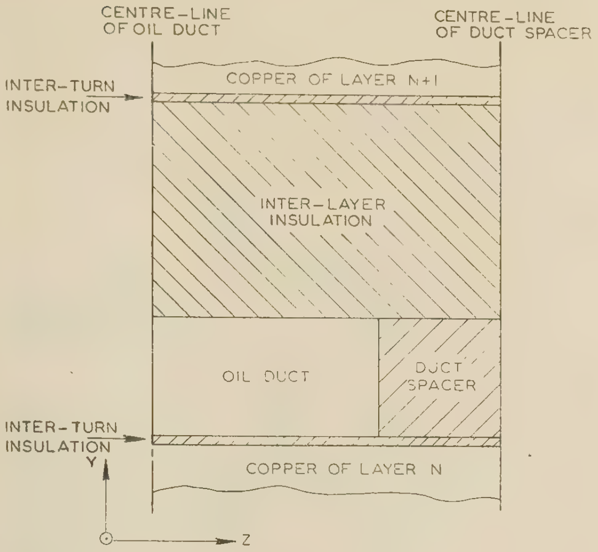


Fig. B.—Elemental thermal system for layer type transformer winding.

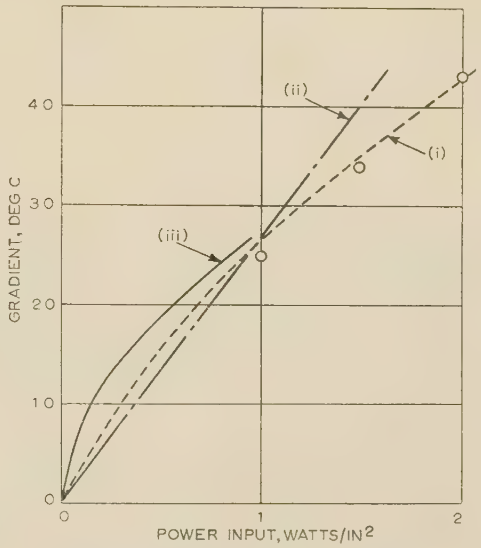


Fig. C.—Copper-to-oil gradients.

(i) From Fig. 6 of paper.
(ii) No distortion of velocity profile.
(iii) From tests on a transformer.
O Calculated values for copper at 95° C.

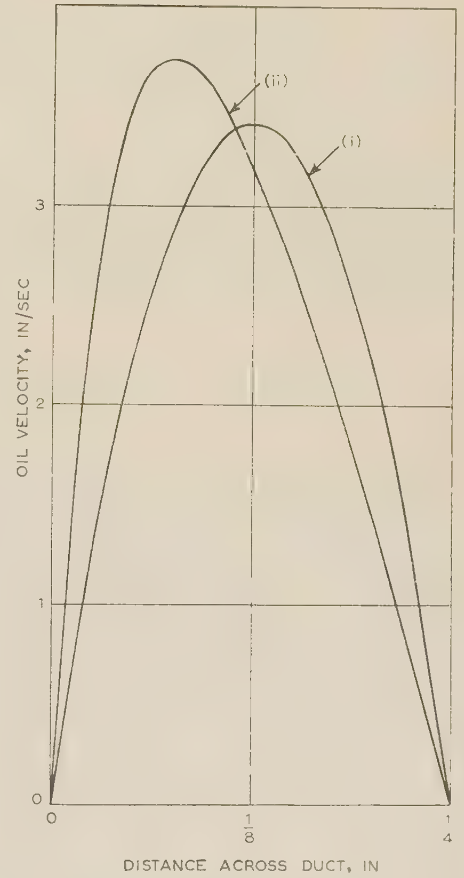


Fig. D.—Distortion of velocity profile due to viscosity and density changes.

(i) Isothermal case.
(ii) At surface thermal flux of 2 watts/in^2.

actual system is composed of circumferential repetitions of an element of the type shown in Fig. B (curvature neglected) alternating with its mirror image.

Even if the rectangular oil duct possessed highly conducting walls, the heat-transfer coefficient would vary around its periphery.[B] The duct spacer material has a higher thermal conductivity than both paper and oil, while the thermal conductivity of paper is much greater in the circumferential (z) than in the radial (y) direction. Thus the heat transfer from the interlayer insulation side of the duct cannot be neglected, and even in the complete absence of duct spacers would amount to about 20% of the total. Evidently, the correct division of the duct space between oil and spacer is important and 'allowance for the paper insulation' is not the simple matter implied in the paper.

A solution of the problem has been given.[C] This involves, first, determination of the thermal properties of the materials involved, and secondly, the solution of the governing equations. These are, for heat flow that due to Fourier,[D] and for velocity distribution that of Navier.[E] Both can be solved by successive approximation, numerically or using a resistance network analogue, and employing simplifying assumptions, due to Clark and Kays,[B] for constant thermal flux conditions.

Such an analysis can be applied to the $\frac{1}{4}$ in duct of the present system. Numerical solution of the finite-difference equations obtained by dividing the duct into ten gives the values plotted as points on Fig. C. Curve (i) is from Fig. 6 of the paper for 30° C bulk oil. Curvature of the annulus was neglected and the mean copper temperature was taken as 95° C. Changes in oil velocity distribution due to viscosity and density variation with temperature were included.

Using this approach, the concept of a 'narrow film' of oil 'adjacent to the surface' moving at relatively high velocity can be clarified. Fig. D gives velocity profiles for a given pressure gradient along the annulus. Profile (i) is the parabolic one for the isothermal case, while profile (ii) is that due to the combined effect of density and viscosity change at a duct-wall thermal flux density of 2 watts/in^2. The maximum velocity increases by less than 10% but it is displaced by about 40% towards the hot surface. This displacement lowers the thermal resistance, which is not appreciably affected by mean oil flow rate. Were the velocity distribution to remain parabolic, this resistance would

be constant as shown by curve (ii) of Fig. C. When all sides of a rectangular duct are transferring heat, the concavity of such curves is greatly increased as shown in curve (iii) of Fig. C, obtained from an actual transformer and including the temperature drop through the solid insulation.

References

(A) Weed, J. M.: 'Temperature Gradient in Oil Immersed Transformers', *Transactions of the American I.E.E.*, 1911, **30**, p. 427.

(B) Clark, S. H., and Kays, W. M.: 'Laminar Flow Forced Convection in Rectangular Tubes', *Transactions of the American Society of Mechanical Engineers*, 1953, **75**, p. 859.

(C) Allen, P. H. G.: 'The Distribution of Temperature in a Layer-Type Transformer Winding', *Proceedings of the B.T.H. Third Summer School in Electrical Engineering*, 1956, p. 47.

(D) Fourier, J.: 'Mémoire d'analyse sur le mouvement de la chaleur dans les fluides', *Mémoires de l'Académie Royale des Sciences de l'Institut de France*, 1833, **12**, p. 507.

(E) Navier: 'Mémoire sur les lois du mouvement des fluides', *Mémoires de l'Académie des Sciences* (2nd series), 1823, **6**, p. 389.

Messrs. E. D. Taylor, B. Berger and **B. E. Western** (*in reply*): It is a fault in the presentation of the paper, to which Mr. van Bueren rightly calls attention, that thermal conductivity is disregarded. We agree that in those regions where $d^2({}_c\Theta_h)/dh^2$ is finite, errors in calculating f_{ch} will arise. The regions concerned are those where the oil temperature changes gradually across the width of the duct such that it is impossible to define the bulk oil temperature precisely, as for example at the bottom of each coil. In such regions the definition of heat transfer coefficient is meaningless, since a change in oil thermocouple position alters the calculated value of f_{ch}. We had recognized this and had dotted the top and bottom of the convection coefficient distributions of Fig. 5. The error at the top of the 3 ft and 5 ft coils is, however, negligible, as was shown experimentally by using the small heaters described in Section 3.1.

The curves of Fig. 3 and 4 have not been adjusted in any way for ambient temperature (indeed the cooling coil mentioned in Section 3.1 supplied a completely artificial ambient temperature) and this is, of course, the explanation of such apparent inconsistencies as occur in some of these curves. The point that the paper is making is that the shape of the oil temperature distribution has a general form, but that the extremities are determined by the external tank conditions, including ambient. Thus in analysing the data of an individual transformer, ambient conditions must be specified, as Mr. van Bueren points out, but for the general gradients this is not necessary.

The oil flow above the transition point is certainly not turbulent in the sense in which the term is usually understood with flow in ducts. Here the transition is characterized by a rapid change from a parabolic profile at the entrance to an almost stationary oil bulk and a thin rapidly ascending oil stream close to the surface. Above the transition region it is as if there occurred an oil 'slip' bounded on one side by stationary oil and at the other by the coil surface. The picture is substantially the same for open coils except that the drift of bulk oil at right angles to the coil surface establishes the fast stream more readily. Experimental studies of oil flow patterns in our laboratories confirm the general picture outlined above.

The correlation of the results for vertical-layer windings was included in the paper for the sake of completeness. We feel that the usefulness of correlation is greatly overrated.

It is interesting to note the success Mr. Allen has had with his theoretical approach in his most relevant contribution. Both he and Mr. van Bueren stress the difference between 'bilaterally' and 'unilaterally' heated ducts. There is, however, no loss of generality in deriving the gradient curves of Fig. 6 from experiments on unilaterally heated ducts, because the heat-transfer mechanism is confined to the fluid layers near the surface. This is indeed implied in the very definition of a gradient surface to fluid. The solution of a bilaterally heated duct is a simple combination of the gradient curves of Fig. 6 and the laws of heat conduction. On the experimental side, we have worked on ducts heated on both sides as, for example, in the transformer described in the last paragraph of Section 6.1. These ducts behave in a very similar manner to 'unilaterally' heated ducts.

INDEX TO VOLUME 105 PART A

1958

ABBREVIATIONS

(P)—Address, lecture or paper.
(p)—Subject dealt with in a paper or address.
(D)—Discussion on a paper.
(A)—Abstract of paper or address.

A

B

C

D

E

F

G

H

T

U

V

W

Printed n Great Britain by
UNWIN BROTHERS LIMITED, WOKING AND LONDON

PROCEEDINGS OF THE INSTITUTION OF ELECTRICAL ENGINEERS

Part A. POWER ENGINEERING, DECEMBER 1958

CONTENTS

Declaration on Fair Copying.—Within the terms of the Royal Society's Declaration on Fair Copying, to which The Institution subscribes, material may be copied from issues of the *Proceedings* (prior to 1949, the *Journal*) *which are out of print and from which reprints are not available.* The terms of the Declaration and particulars of a Photoprint Service afforded by the Science Museum Library, London, are published in the *Journal* from time to time.

Bibliographical References.—It is requested that bibliographical reference to an Institution paper should always include the serial number of the paper and the month and year of publication, which will be found at the top right-hand corner of the first page of the paper. This information should precede the reference to the Volume and Part.

Example.—SMITH, J.: 'Overhead Transmission Systems,' *Proceedings I.E.E.*, Paper No. 3001 S, December, 1954 **102 B**, p. 1234).

THE BENEVOLENT FUND

During the last few years the amount received from subscriptions and donations has been insufficient to meet the cost of grants and management charges. The deficiency is met by making encroachments on capital funds. This may one day prove to be disastrous unless it is checked. Will you help to ensure that the income from subscriptions exceeds outgoings?

Subscriptions, preferably under Deed of Covenant, and Donations may be sent by post to

THE HONORARY SECRETARY
THE INCORPORATED BENEVOLENT FUND OF THE INSTITUTION OF ELECTRICAL ENGINEERS, SAVOY PLACE, W.C.2
or may be handed to one of the Local Honorary Treasurers of the Fund.

Though your gift may be small, please do not hesitate to send it

☆

LOCAL HON. TREASURERS OF THE FUND:

EAST MIDLAND CENTRE . . . . *R. C. Woods*
IRISH BRANCH . . . . *A. Harkin, M.E.*
MERSEY AND NORTH WALES CENTRE *D. A. Picken*
NORTH-EASTERN CENTRE . . . *J. F. Skipsey, B.Sc.*
NORTH MIDLAND CENTRE *E. C. Walton, Ph.D., B.Eng.*
SHEFFIELD SUB-CENTRE . . . . . . *F. Seddon*
NORTH-WESTERN CENTRE *E. G. Taylor, B.Sc.(Eng.)*
NORTH LANCASHIRE SUB-CENTRE *G. K. Alston, B.Sc.(Eng.)*
NORTHERN IRELAND CENTRE . . *G. H. Moir, J.P.*
SCOTTISH CENTRE . . . . *R. H. Dean, B.Sc.Tech.*
NORTH SCOTLAND SUB-CENTRE . . . *P. Philip*
SOUTH MIDLAND CENTRE *Capt. J. H. Patterson, R.A.*
RUGBY SUB-CENTRE . . . . *P. G. Ross, B.Sc.*
SOUTHERN CENTRE . . . . *G. D. Arden*
WESTERN CENTRE (BRISTOL) . . *A. H. McQueen*
WESTERN CENTRE (CARDIFF) . . *E. W. S. Watt*
WEST WALES (SWANSEA) SUB-CENTRE *O. J. Mayo*
SOUTH-WESTERN SUB-CENTRE . . . *W. E. Johnson*

Published by The Institution, Savoy Place, London, W.C.2. *Telephone:* Temple Bar 7676. *Telegrams:* 'Voltampere, Phone, London.'
Printed by Unwin Brothers Limited, Woking and London.